CANMET

National Uranium Tailings Program
Energy, Mines and Resources Canada

Canadian
URANIUM
Mill Waste Disposal Technology

Steffen Robertson & Kirsten (B.C.) Inc.
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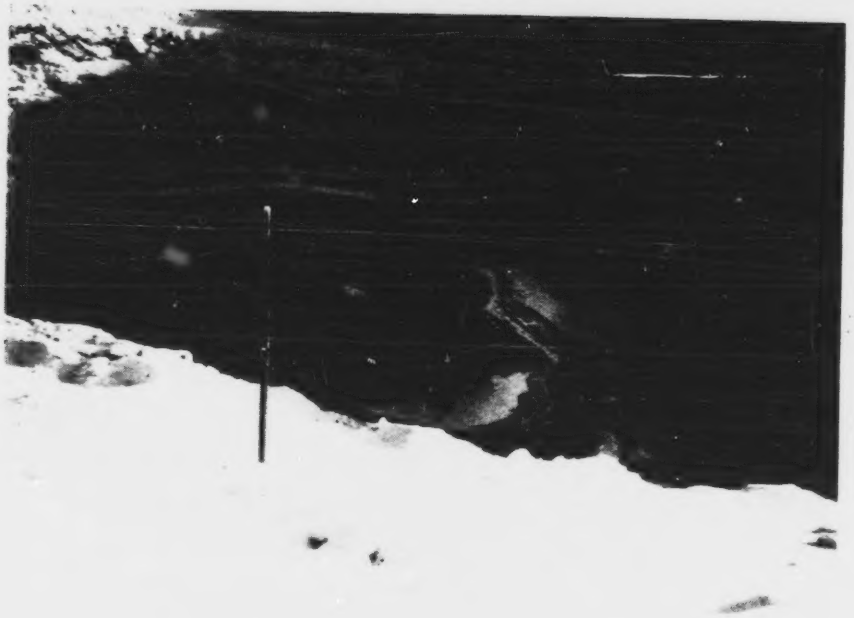

In-pit disposal of uranium tailings at Rabbit Lake, Saskatchewan. Tailings and raffinite are reduced to 45% solids by thickening and filtration.

CANADIAN URANIUM MILL WASTE DISPOSAL TECHNOLOGY

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ENERGY, MINES AND RESOURCES CANADA

Canada Centre for Mineral and Energy Technology
555 Booth Street
Ottawa, Ontario K1A 0G1

Prepared by:

STEFFEN ROBERTSON AND KIRSTEN (B.C.) INC.
#801 - 1030 West Georgia Street
Vancouver, B.C. V6E 2Y3

in Association with

SENES CONSULTANTS LTD.
499 McNicoll Avenue
Willowdale, Ontario M2H 2C9

MELIS CONSULTING ENGINEERS LTD.
519 - 45th Street West
Saskatoon, Saskatchewan S7L 5Z9

Principal Authors: A. MacG. Robertson
R.A. Knapp
L.A. Melis
N.A. Skermer

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MICROMEDIA

"Radium the mystic virtue of vivid decomposition"

D.H. Lawrence

INTRODUCTION

In 1982 the National Uranium Tailings Program (NUTP) began the process of bringing together the knowledge, developing technical understanding of uranium mine and mill wastes, and developing mathematical modelling systems that would predict future behaviour. The program was organized in three parts: modelling, measurement, and disposal technology.

This document summarizes the findings of the disposal technology part of the program. It is not necessarily comprehensive or precise. Some technologies, such as lake disposal, were not adequately researched. However, all the elements of currently applicable technology are addressed. Application to specific Canadian sites is in general terms only. Deposition or close-out technologies are the responsibility of the property owners and regulatory agencies. What follows in this manual is frequently the professional opinion of the contractor consortium. These opinions, while most are believed to be correct, do not necessarily reflect the policy of the Government of Canada, the Governments of the Provinces, or various agencies. Regulation and disposal technology of wastes are evolutionary and cannot be defined precisely.

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SUMMARY

All segments of society are concerned with disposal of uranium mill tailings, and the safe and economic closure of tailings deposits. People living near tailings deposits want the reclaimed facility to remain stable and not detrimentally affect their health; fish and game officers want to preclude pollution of surface and ground waters by uranium tailings deposits; regulators have a social obligation to society to ensure that appropriate technology is employed in the operation and closure of deposits; the consultant must be aware of and must use acceptable technology; and the industry that pays the bill wants an economic way to leave the deposit and at the same time fulfill its obligation to society to care for the complete cycle of mine development and closure.

This manual is intended for all those people. At the expense of being all things to all people, it sets out aspects of the present state of technology in the design, operation and closure and reclamation of uranium mill tailings deposits, it reviews design objectives, and compares and recommends some appropriate technologies for designing and implementing economic operating and closure works at Canadian uranium mill tailings deposits. The technology presented is based substantially on the work done and results obtained from the National Uranium Tailings Program (NUTP) administered by CANMET (Canadian Centre for Mineral and Energy Technology). It does not encompass all technology but concentrates on those aspects which may be characterized as engineering and construction technology for site development, closure, maintenance and surveillance in Canada.

The lay person living near or potentially affected by operating, closed or reclaimed Canadian uranium mill tailings deposit may peruse this document for a description of typical Canadian deposits. From reading this manual he may understand the requirements of closure and reclamation, and be assured that what is done at the deposit of concern to him is done properly and to standards consistent with national and international practice.

The fish and game officer can read this manual to appreciate the engineering controls that may be applied to the pathways by which gases, solids and seepage from a uranium mill tailings deposit enters the environment and the natural chain linking plants, animals, and humans. And, having read the manual, he should be able to contribute to a meaningful debate on the operation, closure and reclamation of existing deposits and the planning for new facilities.

The regulator charged with establishing and maintaining programs wants to know what is being done in uranium mill tailings facilities operation and reclamation, he wants to know what other political and legal jurisdictions are doing, and he must be certain that when he reviews and approves a uranium mill tailings operation and reclamation scheme he is operating from a basis of knowledge of the best and most current technology. It is his legal and moral obligation to know, to check, and to act correctly on behalf of society. It is his charge to enforce the laws and regulations that society promulagates for its protection. This volume is compiled in order to assist the regulator discharge his obligations to society.

Consultants have the need to keep abreast of current technology, use it appropriately, and in a professional way protect both society and the environment. This volume is of use for these purposes to the consultant in the field of uranium mill tailings operation, reclamation and closure. This manual surveys different technologies, evaluates them, and makes recommendations about appropriate technology.

Industry pays the bill to reclaim and close uranium mill tailings deposits. It must be sure that in so doing it is getting value for money, and that in the future he will not be held responsible for using inappropriate technology today. This manual is intended to survey for the mining company the present state of the art of uranium mill tailings disposal facilities design, operation and closure, present a description of what others are doing, compare the benefits and drawbacks of various systems, and

reassure him that he is undertaking what must be done, but no more, and yet meeting the duty to act as a responsible corporate citizen.

A central theme of this manual is that Canadian conditions are different to those in other countries where uranium mill tailings deposits occur. The cold climate, the vegetation, the terrain, the wet conditions, the remoteness of sites, and the particular Canadian social and regulatory framework demand unique regulatory, technical, and environmental approaches, to proper tailings facilities design, operation and reclamation. This manual draws on the advances, the approaches, and the successes in other countries. It offers a particular Canadian perspective and some guidelines for the application of technologies from other sources to Canadian requirements.

The manual has been set out as follows: First it describes the laws and regulations that govern uranium mill tailings disposal and closure in Canada. From here it broadens to consider what other countries are doing to reclaim and complete remedial works at their uranium mill tailings deposits. In doing this it considers the programs, the technical approaches, and case histories in the USA, Australia, France, and South Africa. Next it surveys the Canadian uranium industry, focussing on uranium milling and tailing management in the various Provinces. At this point proposals are made for general design objectives or criteria that may establish a logical and consistent basis for designing and implementing Canadian uranium mill tailings closure works. The general design objectives borrow from philosophies in other countries, are tailored to Canadian conditions and concerns, and serve, as a central core to unite and focus the needs, desires and objectives of all parties in the uranium mill tailings operations and closure field.

The manual proceeds to describe some of the essential components and technical aspects of successful uranium mill tailings operation closure and reclamation. Four generic Canadian tailings disposal facilities are described followed by a description of appropriate technologies for Canadian conditions which relate to and are evaluated for the four generic sites.

The three sections of the manual that deal with technologies consider: site and deposit characterization, evaluation and selection; design and construction of control structures, liners and covers and control of the major long term disruptive and destabilizing factors of frost action, erosion and acid generation. Each section discusses relevant aspects of the construction, operation closure and reclamation works that enhance protection of people, the environment, and the longevity of the containment works. For each discussion is provided of the need for a particular protection mechanism or entity, the technologies that are required to design the entity, and recommendations made regarding appropriate technical approaches for Canadian conditions.

Once closure is complete, surveillance and long-term maintenance begin. As a design objective it is considered appropriate to reduce the need for human intervention in the future. But no technology exists to preclude future surveillance and maintenance, and it is necessary to plan for it. The section of this manual on that topic draws on experience and programs in other countries, and recommends an appropriate methodology for closed Canadian deposits.

The technology applicable to uranium tailings in Canada is evolving rapidly and new concepts and applications are being applied to deposits on almost a case by case basis. This is demonstrated by the wide divergence from previous technology of the facilities constructed at Key Lake and Rabbit Lake Open pit. None of the newer uranium deposits have undergone the full cycle of development, operation, closure and maintenance and surveillance. Flexibility of approach and technology is therefore favoured in putting forward recommendations or suggestions regarding appropriate technology.

Amongst the abundant literature on tailings technology, this manual provides a basis for future development. It describes Canadian conditions of relevance, interest, or concern. It documents appropriate laws and regulations. It summarizes appropriate international practice. It establishes a uniform set of design objectives for Canadian deposits. Finally the manual surveys technical approaches, recommends some appropriate technical approaches, and demonstrates their viability for generic Canadian situations.

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CHAPTER 1.0
CLOSE-OUT CRITERIA AND OBJECTIVES

Uranium waste disposal technology attempts to satisfy the following objectives:

- during the operating of the mill, it provides for the containment of the wastes at a level sufficient to satisfy the operating constraints imposed on the facility by the regulatory authorities. Containment measures requiring active intervention by the facility operator, such as interception and return, are acceptable, and

- following close-out of the facility, it provides for the containment of wastes at a level of containment which will reduce releases, and the risk of excessive releases, to limits sufficiently low to ensure long-term environmental protection. The release limits and close-out criteria are determined by regulatory agencies based on their assessment of public concerns and an acceptable level of long-term public liability. To reduce public liability it is desirable to minimize the need for long-term monitoring and maintenance. The technology for the assessment of long-term survival of close-out measures, and the consequential contaminant release, is therefore an important part of the regulatory process.

This chapter describes the close-out criteria and objectives, as currently contained in Canadian regulatory requirements or guidelines. These criteria and guidelines are reviewed and discussed.

1.1 REGULATORY STRUCTURE

The mining, milling, processing, sale and transportation of uranium in Canada is controlled by the federal government under the Atomic Energy Control Act. The prime federal agency responsible for uranium mining and milling is the Atomic Energy Control Board (AECB). The major licensing documents include:

- Ore Removal Permit,
- Underground Exploration Permit,
- Site Construction and Development Approval,
- Mining Facility Operations Licence,
- Decommissioning Approval, and
- Abandonment Approval.

The AECB works in cooperation with several other federal and provincial agencies which play a role in the regulation of uranium mines. Federal agencies include Environment Canada which sets standards for effluent quality and Fisheries and Oceans Canada which is mandated to protect fisheries in the receiving waters. The provincial agencies (including departments of environment, natural resources, labour) as a rule set effluent standards, have a major role in the approval of all waste management facilities, negotiate environmental monitoring programs, control ownership of mining leases, and have a major input into the health and safety aspects of all the mining facilities. These agencies also have several approval documents related to the operation of the properties. The province of Saskatchewan has also drafted uranium mining regulations.

The regulatory practice in Canada is to provide broad but flexible guidelines with end objectives stated in terms of health, safety and long-term liability. This allows a flexible approach to be adopted in the development of appropriate engineering and facilities construction to suit the site-specific concerns and conditions. Such an approach, while it puts a greater onus on operations and regulatory authorities alike to evaluate the objectiveness of each option, provides for an effective control system in which advantage can be taken of site-specific conditions and advances in technology to achieve the most cost and environmentally effective solutions.

The alternative of rigid proscription of standards and criteria, while possibly more readily administrated, may not anticipate all conditions and hence requires either inadequate or unnecessarily conservative and cost-effective measures.

1.2 GENERAL

1.2.1 DEFINITIONS

There are a number of terms related to the close-out of a uranium mine which are poorly defined. These terms include, close-out, decommissioning, abandonment, transition period, short term, and long-term. Definition of these terms is reviewed in this section.

Close-out and decommissioning are treated as synonymous terms. Decommissioning includes shutdown, dismantling of the facility, remedial works, reclamation, surveillance and transition phases. Decommissioning is complete when the licensee is permitted to "abandon" the site. Although the licensee has no further responsibility to the federal government after abandoning the site, regulatory institutions may continue to monitor and inspect the site, undertake such remedial measures as may be required from time to time and place institutional controls on acceptable future site uses. The time between site reclamation and abandonment is normally called the transition period. During this period, the licensee undertakes active monitoring to demonstrate that the decommissioned facility is operating as designed. The transition period is complete when the regulatory agencies permit abandonment of the site.

Short term and long-term are often used to mark particular point in time in the life of a facility. Short term usually means the time during which engineering controls can be expected to function. For civil works such as dams, dykes, and earthen covers, this period is expected to last for one hundred or more years. The Beaverlodge decommissioning plan adopted 200 years as the short term time period. Long-term refers to all time beyond the short term up to 10,000 years. These time scales are not definitive but provide boundaries for modelling the environmental effects of a facility.

1.2.2 ATOMIC ENERGY CONTROL BOARD (AECB)

The AECB regulations prohibit a licensee from abandoning a uranium mining facility except under written approval of the AECB. Although the AECB does not have specific regulatory requirements for decommissioning, they have proposed regulatory policy statements for decommissioning nuclear facilities. The most recent policy statements have been issued as consultative documents C-90, 1985 and C-104, 1986.

Consultative document C-90 describes the AECB "Policy on the Decommissioning of Nuclear Facilities." This policy is outlined below in point form:

- all new facilities and all existing facilities must provide a conceptual decommissioning plan before issuance of their first or renewed operating licence. This plan must include a description of the works and the plans for financing the decommissioning. Updates should be submitted as the plan changes,

- a detailed plan is required one year before the end of operations,

- if the plan requires long-term institutional control, the AECB will review the justification. As a general policy, controls which require active human intervention are not acceptable while passive mechanisms such as land use controls may be acceptable, and

- upon gaining approval to abandon the site, all obligations under the AECB regulations are fulfilled.

Consultative document C-104 provides the "Regulatory Objectives, Requirements and Guidelines for the Disposal of Radioactive Wastes." The AECB objectives for waste disposal are to minimize any burdens placed on future generations, protect the environment and protect human health, taking social and economic factors into account.

The Board further outlines the requirements to meet these objectives, as follows:

A. Burden on Future Generations

The burden on future generations shall be minimized by:

- selecting disposal options for radioactive wastes which, to the extent reasonably achievable, do not rely on long-term institutional controls as a necessary safety feature,
- implementing these disposal options at an appropriate time, with technical, social and economic factors being taken into account, and
- ensuring that there are no future radiological risks to human health that would not be currently accepted.

B. Protection of the Environment

Radioactive waste disposal options shall be implemented in a manner such that there are no future radiological impacts on the environment that would not be currently accepted and such that the future use of natural resources is not impaired by either radioactive or non-radioactive contaminants.

C. Protection of Human Health

a) Requirements in the Absence of Institutional Controls

For a disposal facility where long-term institutional controls are not required as a safety feature, the predicted radiological risk to individuals shall not exceed 1×10^{-6} serious health effects in a year.

b) Requirements in the Presence of Institutional Controls

For a disposal facility where long-term institutional controls are required as a safety feature, the predicted radiological risk to individuals may exceed 1×10^{-6} serious health effects in a year if:

- this is compatible with the results of optimization considerations, and
- provided that the predicted radiological risk to individuals does not exceed that which is presently accepted from current operations involving the same wastes.

The basic tool for assessing requirements for reclamation works is predictive modelling with a radiological pathways analysis model. As noted above, in those cases where institutional controls are required (i.e. risk exceeds 1×10^{-6} serious health effects/year) an optimization (cost-benefit) analysis is required.

1.2.3 THE PROVINCE OF ONTARIO

The Province of Ontario plays an active role in the licensing, monitoring and regulation of uranium mines. Under the Ontario Water Resources Act, the Ontario Ministry of the Environment has extensive powers to regulate water supplies and waste disposal facilities. The major written policy documents are "Water Management - Goals, Objectives, Policies, and Implementation Procedures" and "Objectives for Environmental Control in the Ontario Mineral Industry". These criteria documents provide specific objectives for effluent and receiving water quality.

With respect to closeout or decommissioning, the Province of Ontario sets generic requirements in the "Guidelines for Environmental Control in the Ontario Mineral Industry" document, 1979 Part D: Abandonment. These criteria are listed below:

D-1 All mine-mill structures should be completely dismantled. The resulting material should be removed from the property or should be disposed of in a suitable manner.

D-2 All mine-mill machinery etc., should be removed from the property or, if this is not practicable, should be collected and disposed of on the property in a suitable manner. All such waste, for instance, could be collected in a common area and covered with soil (spoil from the pit area, etc.). The resulting mound could be easily revegetated. Perhaps this type of waste could be taken to a gravel pit, etc., on the property and, at a suitable time, could be buried. Any small open pits on the property could serve as burial areas.
The possibility of groundwater contamination should always be kept in mind when waste materials are to be buried.

D-3 Whenever and wherever possible and practicable, waste rock or, in general, spoil piles should be graded to below mature tree level. Where this is impossible, waste piles should be kept as low as possible.

D-4 Where garbage from a townsite etc., has been permitted to accumulate, the garbage should be covered with earth and revegetated before the property is abandoned.

D-5 Tailings areas, tailings dams, waste rock dumps, and mill sites etc., should be revegetated in an approved manner.

The Province provides input to the AECB on decommissioning proposals. A prime objective for the Province is, however, to ensure that long-term liability remains with the mining company. Therefore, even though a proponent may gain AECB approval to abandon the site, there are no written policies that state the Province may take over the long-term liability for the site.

1.2.4 THE PROVINCE OF SASKATCHEWAN

The Province of Saskatchewan plays an active role in the licensing, monitoring and regulation of uranium mining operations. Under the Water Resources Management Act, the Province issues Certificates of Approval to operate all industrial waste treatment facilities and water treatment/supply systems. These approvals may contain numerous conditions including monitoring requirements, effluent and emission standards, operating guidelines, reporting requirements, etc.

The Province also has developed draft regulations called "Uranium Mining Pollution Control Regulations." These regulations specify conditions for approval to construct the mining works. Conditions include environmental study requirements, design requirements, contingency procedures, effluent quality criteria as well as requirements for reclamation and abandonment. These regulations have been internally revised but never released. The specified conditions for a tailings area as stated in part (d) of Section 20 of the 1980 draft regulations are as follows:

Unless otherwise approved by the Minister, upon shut-down of a milling operation or waste management facility, the owner or operator of the mill shall stabilize and reclaim the waste management facility by:

(i) providing drainage controls to limit fresh water into the waste management facility to direct precipitation,

(ii) removing as much surface water from the facility as possible and providing for drainage such that there is no permanent water pond over the solid waste materials,

(iii) monitoring of any seepage or discharge from the facility, and providing for treatment of any seepage or discharge from the facility, if the levels of substances in the water are above the maximum monthly mean concentrations as listed in Schedule 1,

(iv) grading of the solid waste materials and covering with sufficient soil, overburden, or other material to produce a calculated surface exhalation of radon from the tailings of less than 2 $pCi/m^2/s$. (cover depth of no less than 3 metres and composed of the same material as surrounding soils, as far as radioactivity is concerned),

(v) providing a fully self-sustaining vegetative cover over the cover materials and tailings,

(vi) providing wind and water erosion control on any sloped surfaces such as embankments, rip-rap and/or vegetative cover,

(vii) providing barriers (fences) and notification to limit public access to the area.

With the Beaverlodge decommissioning, some of these conditions were not applied and it is reasonable to predict that future decommissioning plans will vary from these requirements. The intent of the draft regulations to minimize erosion, reduce radon emanation, reduce surface gamma levels, minimize water contamination and limit public exposure and access remains valid.

The final pertinent provincial responsibility is the application of the Water Quality Objectives which specify ambient surface water quality for receiving waters. These normally apply at a specified point of control downstream of the decommissioned facility.

The Province plays an active role in the review of decommissioning plans and has agreed to take over long-term monitoring of the facilities if, at the end of the transition period, the plan meets all objectives as set by both the Province and the AECB (i.e. the AECB gives approval to abandon). This contrasts with the approach to long-term liability taken by the Province of Ontario.

1.3 GENERIC CLOSE-OUT REQUIREMENTS

1.3.1 GENERAL

The requirements for close-out of a uranium mine in Canada are highly site dependent. The primary requirements focus on the long-term health and safety of the public. Therefore, it is the responsibility of the proponent to develop a plan that meets the generic requirements of the AECB. There are no specific requirements relating to cover depths, acceptable downstream slopes for dams, radon emanation, etc. The provinces do, however, have specific requirements for effluent discharges and downstream water quality.

Some of the major issues relating to long-term management of uranium tailings are discussed in the next section.

1.3.2 GENERIC REQUIREMENTS OF REGULATORY AUTHORITIES IN CANADA

The following "generic requirements" are a summary of the global regulatory requirements in Canada.

i) Radon Control

There are no specific requirements for radon control. The need for radon control is determined through an environmental pathways analysis. If radon is a major exposure pathway (which in Canada has not been the case to date) the requirements may be determined through a cost-benefit analysis. Although direct control for radon may not be required, the AECB have also stated that radon control should be considered when designing other reclamation works such as a gamma radiation attenuation cover (AECB undated).

ii) Attenuation of Gamma Fields

There are no specific requirements for attenuating gamma fields. With the decommissioning of the Beaverlodge uranium mine, the AECB did require surface gamma fields to be reduced to 2.5 μS/h. The need for further reductions below 2.5 μS/hr were to be assessed through a cost-benefit analysis (AECB undated).

iii) Spills

Tailings spills as a general rule should be excavated and disposed of in the tailings area (AECB undated). A proponent may propose to leave spills in place if it can be demonstrated that: their presence represents minimal concern; their removal would cause excessive environmental damage; or the cost for removal and relocation exceeds the benefits. Therefore each spill should be treated on an independent basis.

iv) Dam Stability/Engineering Principles

It is recognized that structures have a finite lifetime and degrade over time. With this in mind, the AECB has not dictated any definitive criteria for downstream slopes, etc. For the Beaverlodge close-out three conditions were imposed for structures:

- The use of passive barriers, natural or engineered, should be maximized to control radioactive and non-radioactive releases from the closed-out site,
- The use of containment systems which may be subject to abrupt degradation of performance should be minimized and preference should be given to systems which only degrade gradually, and
- All containment systems must be evaluated in terms of their long-term performance and durability. Reliance on maintenance should be minimized.

v) Effluent Releases

Discharges from a closed-out facility would normally be required to meet the Federal Mining Effluent Regulations and the Provincial Discharge Objectives. Where it can be demonstrated that control to these limits is not practical, the provinces have made allowance for mixing zones. At the boundary of this zone, receiving water must either meet provincial water quality objectives or a negotiated set of site-specific objectives.

vi) Seepage Control

The control of seepages is a highly site-specific requirement. Where seepages result in unacceptable levels of downstream contamination, controls are required. On the other hand, it may be advantageous to allow infiltrating waters to exit as seepage, thus taking advantage of the retardation capabilities of the local natural materials.

vii) Perpetual Care

It may not be economically practical to implement a decommissioning plan that permits the site to be abandoned. For these specific applications a perpetual care option may be practical. AECB consultative document C-90 states "controls which require ongoing human intervention (as would be required for effluent treatment) will not be acceptable."

viii) Institutional Controls

Institutional controls are recognized as a most likely requirement for abandoned uranium mill tailings areas. The need for controls must be justified and demonstrated (through a cost-benefit analysis).

1.3.3 RADIOLOGICAL PROTECTION STANDARDS/PRINCIPLES

There are three basic radiological principles that are applied to all nuclear facilities:

- the effective dose equivalent to any person arising from the site at any time should not exceed 5 μSv/yr,
- the effective dose equivalent for occupational exposure should not exceed 50 μSv/yr, and
- any exposures arising from the site should be kept as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle).

CHAPTER 2
INTERNATIONAL PRACTICE

Over the past ten years, concerns regarding the environmental impact of the uranium mine wastes have resulted in dramatically increased levels of impact evaluation and regulatory control in the leading western world uranium producing countries. This has resulted in a considerable advance in the technology of uranium waste disposal and stabilization. Advances have generally been uneven depending on:

- the economic value of the uranium resource,
- the level of public and regulatory concern, and
- levels of funding made available for technology development.

The U.S.A. has led in much of the technology development, mainly as a result of research sponsored by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) in its administration of the Uranium Mill Tailings Remedial Action Project (UMTRAP). Canada has made large contributions, both through developments by the uranium mining industry and federal government sponsored research, notably the National Uranium Tailings Program (NUTP). Significant contributions have been made by countries such as Australia and France. Many of these contributions are biased toward the concerns and regulatory practices in the contributing country and may not be directly applicable or appropriate to Canada.

This chapter reviews regulatory practices and the trends in disposal and close-out technology in the different countries. Methods of close-out technology development are reviewed and a description given of the procedures used to evaluate close-out technology. An understanding of the regulatory environment under which the technology is developed and implemented is a necessary prerequisite to assessing the value of the respective technology to Canada.

2.1 GENERAL

2.1.1 TRENDS IN CLOSE-OUT PROCEDURES

As early as the 16th century in Central Europe miners working uranium bearing ores appeared to be more susceptible to pulmonary disorders than in other mines. Later in 1879 these diseases were diagnosed as lung cancers. An ever-increasing awareness of the effects on health of radiation from uranium ores and wastes has been the primary concern in the development of regulatory requirements and the technology for their attainment. In this regard the concerns pertaining to uranium mine wastes and tailings initially differed significantly from those applicable to other metal mines. Consequently regulatory and technological developments have often been pioneered in the uranium mining industry, particularly in recent years. This technology has been extended to other minerals mining as it became apparent that many of the concerns, and the appropriate technology, are common.

The U.S. experience dates from the beginning of the 20th century with the mining of uranium on the Colorado Plateau. Two periods of activity developed in the U.S.A. The first was radium extraction from 1906-1922 in S.W. Colorado and S.E. Utah with large scale production beginning around 1914, (Landa 1981). Many of the early reduction plants were located in eastern states - Pennsylvania, New Jersey and New York. The second period commenced in the 1940's with the mining of uranium and vanadium to meet the U.S. military needs and for electrical power generation. Currently the latter phase of activity is slowing down.

The Atomic Energy Commission (AEC) which was formed in the U.S.A. in 1946, was responsible for peaceful and military uses of atomic power. But in the opinion of Cook (1980) "the secrecy that enveloped the weapons aspects of the Commission's activities seemed often to become a useful cloak to prevent inquiry into its peaceful operations." According to him "this arrangement persisted for almost 29 years".

Perhaps this accounts for the initial trends in disposal and close-out technology, which were concerned merely with immediate health problems, such as lung cancer in mine workers or mill operators. Only in the last decade has the approach been shifted to a concern for long-term effects.

The AEC is now known as the NRC. Scarano, at that time the Chief of the Licensing Branch of the NRC, stated that they did not set about the uranium tailing issue in earnest until late 1976, (Scarano 1980). They did so by setting guidelines for the industry, formulating them in the shape of performance objectives for tailing management. Within this framework industry was allowed considerable flexibility to develop management alternatives.

To a large extent this flexibility was granted to an industry that was probably more familiar with the problems than anybody, and in many cases had been making serious attempts to develop technical solutions. In recent years industry has developed a wide range of methods and solutions in response to regulatory concerns. In the case of abandoned tailings piles, however, the state inherited the problems and government sponsored research programs are seeking to develop solutions. Such a program is the UMTRAP currently being carried out by DOE.

Gradually, as the long-term implications of uranium tailing disposal sank in the public and institutional mind increasing emphasis has been placed on the development and application of appropriate methodology and technology. The problems involve more than just static considerations, since long-term dynamic processes, such as erosion, weathering and climate change for example, are involved. Given the long periods into the future over which concerns persist and for which control technology must be effective, it is recognized that current technology must be re-evaluated for its long-term effectiveness. Risk and probability concepts can be used, but with a very short-period, imperfect data base in many cases, we are left with considerable uncertainty.

Beyond the immediate, close-range effects on humans wider environmental issues are at stake. The principal concern is surface and groundwater, but soils, vegetation, wildlife, land use and in some places cultural, scenic and wilderness resources are affected. In the U.S.A. these environmental concerns are expressed in various laws, regulations and executive orders through acts such as the National Environmental Policy Act (NEPA) of 1969. Control is through the NRC in issuing licenses authorizing uranium milling activities.

The physical size of the problem is demonstrated by the approximately 200 million tons of tailings from uranium production in the U.S.A., (Caldwell & Robertson 1986). The corresponding figure in Canada is 150 million tons, (SRK 1986). These quantities are small by comparison with other tailings which contain significant quantities of uranium but from which uranium is not necessarily extracted such as the gold/uranium tailings of South Africa or the phosphate tailings in Florida.

In the U.S., at the present time (1987), no new uranium mines are being developed and the concern there is largely with ensuring that hazards from existing uranium piles are minimized. Since U.S. remedial work constitutes the main source of information outside Canada it is considered in some detail later.

2.1.2 REGULATORY FRAMEWORKS IN OVERVIEW

The regulation of uranium tailings management is still in a state of development, especially since the goals are long-term. In the development of an effective and workable regulatory framework, it is difficult to try to balance philosophical, socio-economic and technical issues. Mill operators are often justifiably wary of overzealous regulators whose requirements impose unnecessary costs out of all proportion to the problems that exist, or else they find themselves left with vague guidelines offering little help when management needs to make decisions. Nevertheless the common goal of both regulators and operators ought to be safe and economical tailings management.

Regulatory requirements in the U.S.A. are complex and onerous. The United States set out jurisdiction in the Uranium Mill Tailings Radiation Control Act (UMTRCA) passed by Congress in 1978 and amended in 1981. Therein the responsible agencies named are the DOE, the NRC and the Environmental Protection Agency (EPA). Mill tailings are controlled federally by the NRC with the exception of 26 "Agreement States", (Montgomery 1979) where some regulatory authority is vested in the state government. However, states regulating tailings must do so to standards no less stringent than federal requirements.

It is worth pointing out that, under the Atomic Energy Act of 1954 and amendments, the basic philosophy is to "minimize danger to life and property". The Uranium Mill Tailings Radiation Control Act in contrast provides explicitly for cost-benefit analysis. This means in practice that the levels of exposure below regulatory concern may be set higher for uranium mill tailings than for low-level radioactive wastes, (Trubatch 1986) for discussion of the legalities.

The standards enforceable by NRC are set by the EPA under the Clean Air Act for maximum permissible radioactive levels in structures, soils, water and air. The DOE is involved in close-out operations as the custodian of all current and future tailings sites, as well as taking care of all the inactive sites that require remedy.

Thus DOE implements the requirements that EPA develops, which NRC enforces.

The U.S. regulatory regime can be compared with that in Canada, where the federal Atomic Energy Control Board (AECB) is responsible for all licensing, regulation and control, co-ordinating with both federal and provincial regulatory bodies on such concerns as water quality. In Canada mineral resources come under the provincial government. Thus two levels of governmental regulatory procedures can apply in a province, as can occur also in a U.S. state. Contrasts exist between the United States and the Canadian uranium tailings piles (Caldwell and Robertson 1987). Similar regulatory situations supported by government Acts exist in Australia, and to some extent in the Republic of South Africa, although in the latter country uranium is not identified separately from other wastes since it is only mined in conjunction with or, as a by-product of, other minerals, mainly gold.

2.1.3 URANIUM INSTITUTE (UI)

The UI is based in London, England and represents roughly 60 corporate members who are either uranium producers or consumers from about 20 countries. Its Working Group has attempted to define some practical working principles as a framework for regulating uranium mill tailings management, (UI 1984). The following 2 extracts from this short document are useful items worth repeating:

> A number of basic facts need to be kept in mind when considering the task of containing and isolating uranium mill tailings.
>
> (a) Compared with the volume of waste arising in other parts of the fuel cycle, the volume of mill tailings is large. In practical terms, it requires that they be deposited at or very near to the mill site. Containment systems must therefore be site-specific.
>
> (b) In its turn - both for safety and economic reasons - the mill can usually only be located within a rather limited distance from the orebody, the location of which is fixed.

(c) In large part the constituents in uranium mill tailings which need to be contained (such as molybdenum, vanadium, selenium and arsenic) are the same as those resulting from many other mining operations and may well constitute the major environmental protection problem.

(d) The difference with uranium mill tailings lies in the higher concentration of radionuclides they contain as compared with other tailings. While that level is actually somewhat lower than it was in the original ore - when the uranium was still present - the radionuclides are more 'available' to the environment when they are in the form of mill tailings.

(e) Unlike some of the non-radioactive contaminants present, a progressive reduction in radioactivity occurs with the passage of time; but for all practical purposes, the half-life of the longest lived isotope (thorium-230 with a half-life of 80,000 years) is long enough to make it necessary to deal with the tailings on the basis that their activity will not diminish significantly over any time-period that is likely to be of interest.

(f) The concentration of radioisotopes is, however, low compared with most nuclear wastes. The problems of safely disposing of large tonnages of low-activity mining waste are thus quite different from those posed by used nuclear fuel or reprocessing wastes, where small volumes of highly radioactive waste are involved.

(g) The main radiation concerns associated with mill tailings arise from the possibility of inhaling the short-lived gaseous isotope, radon-222, or its daughter products, or of contamination via the foodchain resulting from the solubility of radium-226 and uranium.

(h) The engineering techniques used for the management of uranium mill tailings are essentially no different form those employed in other sectors of the mining industry. There is thus a great deal of cumulative experience on which to draw. They depend primarily on physical barriers, and on the inherent stability which can be achieved in the consolidated tailings.

The same document goes on to summarize as follows:

> As a contribution to the task of defining a satisfactory regulatory framework for uranium mill tailings management and containment, the Working Group proposes the following set of general guidelines:

(a) Regulations should permit site-specific factors to have maximum impact on the detailed design of a tailings management and containment facility. The operator should propose and justify a plan on the basis of general criteria and local knowledge.

(b) Subjective factors such as visual and aesthetic appearance, although of great importance, are of a local nature and should not be the subject of general criteria.

(c) A baseline study should be undertaken by the proponent of any project prior to commencing operations to establish the prevailing environmental conditions and to provide design criteria for the containment system.

(d) The Working Group endorses the concept of ALARA - defined as "as low as reasonably achievable, economic and social factors being taken into account." This is imprecise, but is an accepted working principle. Optimization, restricted to timeframes and areas in which meaningful predictions can be made, provides valuable order-of-magnitude guidance.

(e) The Working Group nonetheless proposes that there be reasonable cut-off points below which further reductions should not be sought. These might relate to the pre-existing natural background at the site and a level of risk considered to be insignificant.

(f) Derived release limits provide a site-specific methodology for applying the ICRP*'s recommended maximum dose commitments.

(g) The mill tailings containment system should be designed so that the need for ongoing active waste management after close-out will be minimized. It should therefore depend at that stage on natural or passive barriers which do not require continuing attention by man.

(h) An appropriate objective is that maximum releases to the environment after close-out should be no greater than those enforced during the operational phase.

(i) There should be provision for long-term site control to ensure that desirable precautions concerning use of the tailings and the site are observed; this is likely to require transfer of responsibility for the site to institutional control.

(j) Provisions for decommissioning and close-out should be planned early in the life of the project on the most realistic basis possible and should be up-dated at regular intervals.

(k) To the extent possible, regulatory requirements should be resolved and stabilized to permit responsible long-term planning and to avoid futile expenditure.

Once the basic objectives have been set, one practical approach to arriving at a position which is acceptable to both the operator and the regulatory authority in closing out a tailings site is as follows. The approach is based on the concept that site-specific, rather than generic criteria, are the governing factors.

(a) In consultation, the operator and the regulatory agency will discard all options for closing out the site that are unreasonable or unnecessary, retaining only those having potential application at the site for detailed study.

(b) Pathways analysis for each option will be undertaken to determine the dose to the actual and predicted population living within a reasonable radius of the site.

(c) The costs of implementing each option will be determined through feasibility studies.

(d) The estimated dose commitment for each option will be compared with the cost of its implementation, and the company will determine those which it views as feasible and reasonable.

(e) That option which the company will implement will be determined through discussion with the regulatory agency.

2.1.4 INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)

About 150 countries are members of the IAEA whose headquarters are in Vienna, Austria. Initially they put out a booklet on the management of wastes from uranium and thorium mining, (IAEA 1976). This was prepared by a panel of experts and presented in two parts. The first part was an approved Code of Practice. The second part, although put out under the same cover, was meant as a separate Guide to the Code, and it reflected best available technology at that time. The Code is written in qualitative terms without requiring particular quantitative performance criteria to be met.

---

*International Commission on Radiological Protection.

At a later date (IAEA 1981) they dealt more specifically with the design and siting considerations for the management of uranium mill tailings. This is a far more detailed technical document that can be usefully read alongside this present manual.

2.2 UNITED STATES PRACTICE

Generally speaking U.S. practice in the past has been to dispose of uranium tailings above ground in semi-arid conditions close to where the ore is mined. Current NRC recommendations favour below ground disposal.

2.2.1 REMEDIAL WORK ON INACTIVE TAILINGS

The UMTRCA of 1978 authorized the DOE to undertake remedial actions at a number of uranium processing sites.

The DOE designated 24 sites in 10 states mostly in the SouthWest, see Fig. 2.2.1-1. Each site was assigned a priority rating, high, medium or low, 11 of the sites being high priority. The total cost of clean-up in 1981 dollars was estimated at $320 million to be shared between the Federal Government (90 percent) and the state (10 percent). The cleanup period allowed was 7 years. Delays have now pushed the estimated costs to between $700-900 million, (Crawford 1985).

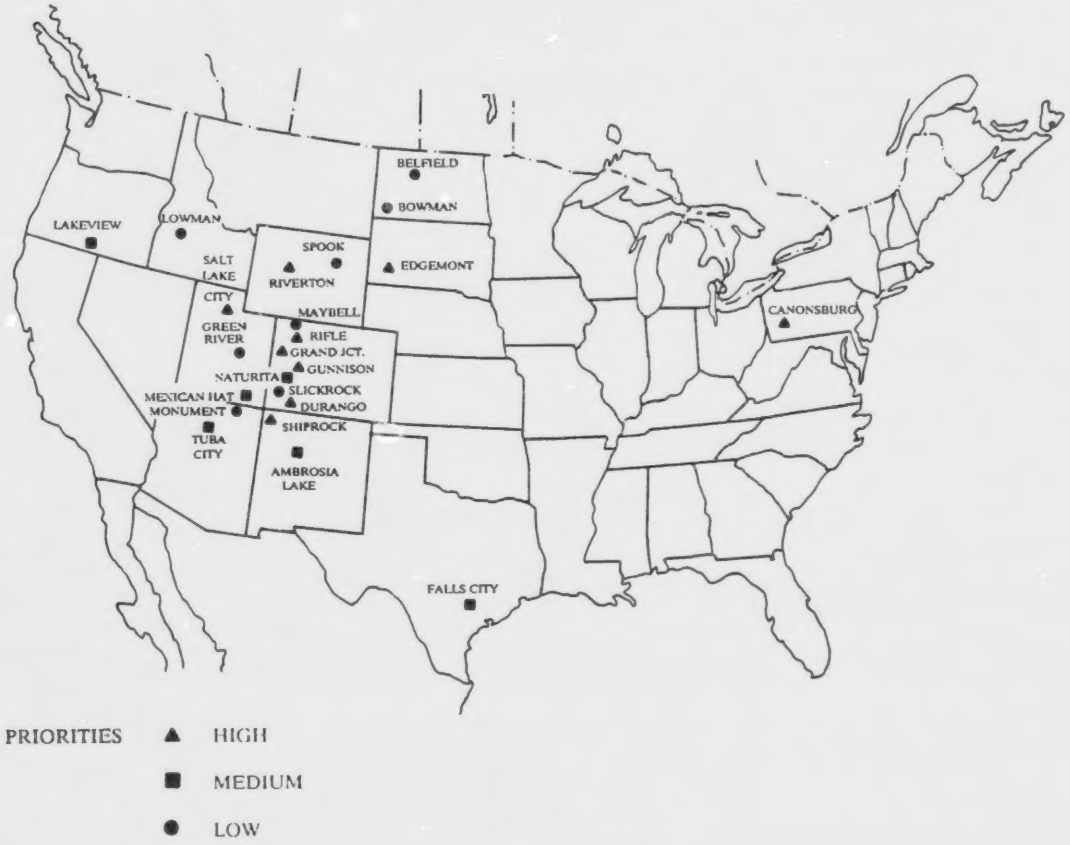

BELFIELD
BOWMAN
LAKEVIEW
LOWMAN
SPOOK
EDGEMONT
SALT LAKE CITY
RIVERTON
MAYBELL
GREEN RIVER
RIFLE
GRAND JCT.
GUNNISON
NATURITA
MEXICAN HAT
SLICKROCK
MONUMENT
DURANGO
SHIPROCK
TUBA CITY
AMBROSIA LAKE
CANONSBURG
FALLS CITY
PRIORITIES
▲ HIGH
■ MEDIUM
● LOW

Figure 2.2.1-1 UMTRA Project Sites

The UMTRA program is well under way, and the entire work at the Canonsburg, PA site is completed. A considerable number of papers detailing specifics of the work have appeared in the proceedings of the annual conferences on management of Uranium Mill Tailings, Low-Level Waste and Hazardous Waste, at Fort Collins, Co, particularly from the years 1982 onwards.

The projects require design for an effective life of 1000 years and in any case at least 200 years. In some cases because of potential geological hazards, such as flood and earthquakes this requires relocation of the tailings. This was the case at the Lakeview site in Oregon, where in place stabilization proved infeasible because of nearby faults and geothermal activity, and the pile was moved about 24 km away to a geotectonically stable site.

The approach to the U.S. remedial work is in four parts each fully detailed in reports obtainable from the appropriate agency.

2.2.1.1 Environmental Impact Statement by the Environmental Protection Agency (EPA)

Source document: "Final Environmental Impact Statement for Remedial Action Standards for Inactive Uranium Processing Sites (40 CFR Part 192)." Office of Radiation Programs, Environmental Protection Agency, Washington, D.C. Vol.s I & II, October 1982, EPA 520/4/82/013-1.

The EPA has established standards to protect the environment and public health and safety from both radioactive and non-radioactive hazards posed by residual radioactive materials at the sites. The standards are for:

- cleanup of tailings that spread from the original site or that were removed and used elsewhere, and

- control of tailings piles to ensure long-term stabilization.

The history of uranium milling in the USA is briefly reviewed showing how the need for remedial action arose. In Grand Junction, Colorado for example, tailings were found to have been used at many locations beneath buildings and for construction of sidewalks.

The amounts and concentrations of radioactivity and toxic materials found in tailings piles and released nearby to air and water are discussed, and estimates made of the extent to which tailings have been moved off the piles by man and by natural forces such as wind and water erosion. Levels of radioactivity in buildings caused by the use of tailings are estimated and compared to natural causes.

The report states the objectives of control measures for tailings piles, and contaminated buildings and lands, and briefly discusses the engineering and institutional controls that are available.

Considerable investigation was made of costs and benefits of:

- alternative standards for control of tailings piles, and

- cleanup standards for buildings and land contaminated by tailings.

Other factors are discussed such as duration and effectiveness of controls and occupational hazard when controls are put into use. The alternative standards for control of tailings that were considered are reproduced in Table 2.2.1-1.

TABLE 2.2.1-1
ALTERNATIVE STANDARDS FOR CONTROL OF URANIUM MILL TAILINGS (U.S.A.)

	Principal Requirements		
Alternative	Minimum Time That Controls Should Prevent Erosion and Misuse (years)	For Radon Emissions from Top of Pile (pCi/m^2s)	For Water Quality Protection
No standards	None (radioactivity decays to 10% in 265,000 years)	No limit (The average emission is 500 pCi/m^2s)	None (Toxic chemicals in tailings at concentrations 100 times background)
EPA Proposed Standard	1,000	2 above background	No increased concentration of toxic chemicals
Alternative A	1,000-10,000	2 above background	No degradation that would prevent present uses
Alternative B	200-1,000	20	Guidance, based on water quality criteria
Alternative C	Indefinite, long-term	100	Guidance, based on water quality criteria
Alternative D	Durable cover; 100-year institutional control; discourage moving of piles	No requirement	Prevent significant erosion of tailings to surface water or groundwater, or treat water before use.
Alternative E	Minimal cover to prevent windblown erosion only; 100- to 200-year institutional control; move only piles in immediate danger due to floods	No requirement	No protection required

In selecting the control standards to adopt three approaches to environmental protection were considered: nondegradation, cost-benefit and least cost. The preferred standard was Alternative B in the table above with control measures selected on a site-specific basis in order to meet relevant water quality criteria for protection of ground and surface water. The EPA Proposed Standard and

Alternative A were believed to be too costly, while Alternative C is no less costly than Alternative B, yet the latter provides greater protection.

The process of implementation of the standards and the resulting effects of the work in terms of health, the environment and economics are considered.

The final wording of the EPA standards is reproduced in Table 2.2.1-2 below.

TABLE 2.2.1-2
EPA STANDARDS

PART 192 - HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM MILL TAILINGS

SUBPART A - Standards for the Control of Residual Radioactive Materials from Inactive Processing Sites

192.02 Standards

Control shall be designed to:

(a) Be effective for up to one thousand years, to the extent reasonably achievable, and, in any case, for at least 200 years, and,

(b) Provide reasonable assurance that releases of radon-222 from residual radioactive material to the atmosphere will not:

(1) Exceed an average release rate of 20 picocuries per square meter per second, or

(2) Increase the annual average concentration of radon-222 in air at or above any location outside the disposal site by more than one-half picocurie per liter.

SUBPART B - Standards for Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites

192.12 Standards

Remedial actions shall be conducted so as to provide reasonable assurance that, as a result of residual radioactive materials from any designated processing site:

(a) The concentration of radium-226 in land averaged over any area of 100 square meters shall not exceed the background level by more than -

(1) 5 pCi/g, averaged over the first 15 cm of soil below the surface, and

(2) 15 pCi/g, averaged over 15 cm thick layers of soil more than 15 cm below the surface.

(b) In an occupied or habitable building -

(1) The objective of remedial action shall be, and reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02 WL. In any case, the radon decay product concentration (including background) shall not exceed 0.03 WL, and

(2) The level of gamma radiation shall not exceed the background level by more than 20 microroentgens per hour.

SUBPART C - Implementation (condensed)

192.20 Guidance for Implementation

Remedial action will be performed with the "concurrence of the Nuclear Regulatory Commission and the full participation of any state that pays part of the cost" and in consultation as appropriate with other government agencies.

192.21 Criteria for Applying Supplemental Standards

The implementing agencies may apply standards in lieu of the standards of Subparts A or B if certain circumstances exist, as defined in 192.21.

192.22 Supplemental Standards

"Federal agencies implementing Subparts A and B may in lieu thereof proceed pursuant to this section with respect to generic or individual situations meeting the eligibility requirements of 192.21."

(a) "... the implementing agencies shall select and perform remedial actions that come as close to meeting the otherwise applicable standards as is reasonable under the circumstances.

(b) "... remedial actions shall, in addition to satisfying the standards of Subparts A and B, reduce other residual radioactivity to levels that are as low as is reasonably achievable."

(c) "The implementing agencies may make general determinations concerning remedial actions under this Section that will apply to all locations with specified characteristics, or they may make a determination for a specific location. When remedial actions are proposed under this Section for a specific location, the Department of Energy shall inform any private owners and occupants of the affected location and solicit their comments. The Department of Energy shall provide any such comments to the other implementing agencies [and] shall also periodically inform the Environmental Protection Agency of both general and individual determinations under the provisions of this section."

Ref: Federal Register, Volume 48, No. 3, January 5, 1983, 40 CFR Part 192.

2.2.1.2 Technical Approach of the Department of Energy (DOE)

Source document: Technical Approach Document, UMTRA-DOE-050425, Albuquerque, New Mexico, May 1986.

This document is concerned with inactive uranium mill tailings sites. It describes the general technical approaches and design criteria that DOE adopts in order to implement Remedial Action Plans (RAPs) and final designs that comply with EPA standards (40CFR192).

There are three basic types of stabilization as follows:

a) Stabilization in place (SIP)
b) Stabilization on site (SOS)
c) Relocation to an alternate site for stabilization.

These three options determine the final location of the tailings but not the final shape of the pile. The final design can vary from above grade disposal to different degrees of below grade disposal.

The main advantage of SIP is a minimal movement of contaminated materials which usually results in it being the most cost effective. It generally consists of consolidating windblown materials and reshaping the sideslopes of the tailings pile. Remedial action primarily involves construction of a cover system over the reshaped pile.

SOS involves handling of all or most of the tailings due to one or more overriding design considerations. Design is such that the stabilized tailings pile is kept within the boundaries of the existing site.

Relocation to an alternative site is necessary if there are fatal flaws in the existing designated site such that long-term or cost-effective stabilization is prevented.

Generalities in the design approach to surface and groundwater and erosion protection, slope stability and settlement, and radon cover introduce the document.

The details of the technical approach are contained in four sections briefly summarized as follows:

a) Surface-water hydrology and erosion protection

It is believed that water erosion is likely to be one of the most disruptive natural phenomena affecting long-term stability. Acquisition of raw hydrological data is by conventional methods. In general Probable Maximum Flood (PMF) and the Probable Maximum Precipitation (PMP) form the basis for design unless it is uneconomic to do so. In addition upstream dam failure of either artificial structures or impoundments caused by natural geomorphic instability are considered. It is recognized that erosion can result from intense precipitation directly onto the tailings pile, runoff from small upland watersheds, and flooding from nearby streams and rivers.

Release of radon gases from tailings piles is a major concern in the reclamation. In order to reduce the escape of the gases into the atmosphere to acceptable levels, the tailings are to be covered with a radon and infiltration barrier. The type and thickness of material used depends on the borrow material available close to the site, and its physical properties.

It is important that the integrity of the radon barrier should be maintained for the design life of the facility (200 to 1000 years). Processes which threaten the integrity of the barrier are wind and water erosion, cracking of the soil due to desiccation, invasion by roots from plants or trees, and animals burrowing into the soil. To protect against or reduce these destructive forces, a rock cover is usually incorporated into the design.

Numerous methods of designing erosion protection are available and these are referenced. Riprap design for top and sideslopes is described together with toe protection and filter requirements.

b) Geotechnical

Geologic characterization of UMTRA sites consists of a summary of the regional geologic setting, local site geology, regional and local structures, Quaternary geology of the site region, and the local distribution of surficial units.

Geomorphic hazards are identified and assessed, to estimate the probability of their occurrence, and to evaluate the magnitude of their effects during the life of the reclamation. The general approach used involves three steps:

- identify past geomorphic processes and estimate their rates from the geomorphic and stratigraphic records (post-glacial time), roughly 10,000 years;

- identify present geomorphic processes and estimate their rates from historic records and field observations (typically less than 80 years); and

- predict future geomorphic processes and rates.

Geotechnical characterization of UMTRA sites is carried out to define the geotechnical conditions of existing tailings piles, foundation soils, and proposed borrow sources. The stratigraphy and physical properties of materials forming the stratigraphic units are characterized. Stratigraphy is determined from boreholes and test pits. Piezocone probings or seismic field studies are also used. Material properties are determined by laboratory tests and field tests. The nature and extent of investigations varies from site to site.

Studies are conduced to define the seismic hazard. These provide a seismotectonic characterization of each site and a set of earthquake design parameters, which include the design earthquake magnitude; on-site peak horizontal ground acceleration; the distances to, and lengths of, capable faults; and the types of capable fault displacement. During the seismic investigation, the potential for on-site fault rupture is analyzed. Based on the findings of the seismotectonic characterization, further earthquake engineering analyses are performed. These analyses may include the development of additional parameters dependent on the local subsurface conditions.

To assess the slope stability of the tailings piles, the long-term static and earthquake loading conditions are determined. Natural slopes which may affect the long-term performance of the embankment are also analyzed for static and earthquake loading conditions using conventional slope stability techniques. In addition, short term static and seismic loading of the embankment slopes and construction slopes are analyzed to assess the suitability of the proposed designs.

The liquefaction potential of the tailings pile and foundations soils under design earthquake conditions is assessed. The liquefaction potential of a site is determine by the soil properties, depositional history, depth to groundwater, and characteristics of the earthquake motion.

For the soils typically encountered at uranium mill tailings sites, liquefaction and/or cyclic mobility can occur only in saturated, cohesionless soils (sands and silts) due to earthquake induced ground motions.

Settlement can occur within the reclaimed tailings pile and in the foundation soils. The settlements depend on the distribution of material types, the compressibility of each soil type, and the stresses on specific soil layers. Settlement, especially differential settlement, can lead to surface runoff concentrations which could erode the pile cover and/or lead to cracking of the radon cover. Settlement is calculated and the cover is designed to avoid damage by settlement.

Experience at early UMTRA sites where tailings are relocated has shown that mixing of tailings during excavation, hauling, and placement results in a uniform embankment after compaction, thus minimizing the potential for differential settlement and eliminating the need for special design and construction considerations.

c) Radon attenuation

Radiological site characterization is performed. The three physical properties of the tailing material which enter into the radon barrier design are radium concentration, emanating fraction, and the diffusion coefficient of radon through the tailings. Of these, the effect of varying the diffusion coefficient (through changes in porosity and moisture content) is less than the other two.

The Technical Approach Document explains means of defining the extent of contamination of the sites, and the design of radon barriers for piles that are to be moved from their present location.

In designing the radon barrier the thickness of cover material required to limit radon flux to 20 pCi/m^2s is calculated using the computer code RAECOM, (NRC 1984). The mathematical model used in RAECOM describes one-dimensional steady-state radon diffusion through a two-phase multilayer system of porous media, representing the tailings pile and its cover.

The proposed cover structure may have several layers consisting of excavated contaminated soil from beneath the pile, windblown material, a compacted radon barrier and rock and gravel erosion protection.

Monitoring of the ambient air concentrations of Rn-222 is performed around the site before, during and after construction of the remedial measures.

The long-term moisture content of soils used in the construction of the cover system is of particular importance in determining the thickness of the radon barrier layer.

A description is given of the laboratory testing, empirical correlations, and computer models used to predict the moisture content versus suction and the long-term moisture content of soils used for the radon barrier and the tailings.

d) Water resources protection

In the United States for most of the uranium production, the acid-leach process is used, and tailing liquors therefore have very low pH values (0.5 to 2). Hydrogeologic characterization including determination of background water quality is required at each of the sites needing remedial work. For purposes of protection of water quality, concentration limits set out in Table 2.2.1-3 are applied, these being consistent with existing national primary drinking water standards.

TABLE 2.2.1-3
PROPOSED EPA INTERIM WATER QUALITY STANDARDS AT UMTRA SITES
(Adopted by DOE)

Constituent	Max Concentration, mg/L
As	0.05
Ba	1.0
Cd	0.01
Cr	0.05
Pb	0.05
Hg	0.002
N (in Nitrate)	10.0
Se	0.01
Ag	0.05
Combined radium-226 and radium-228	5.0 (pCi/L) (0.2 Bq/L)

Subsurface investigations are required to determine the areal and vertical extent of groundwater contamination, and to identify the properties of the geohydrologic units along which contamination may flow. Unsaturated as well as saturated flow is considered. Flow rates and attenuation processes are defined. Surface waters are investigated by stream sampling upstream and downstream of the uranium mill sites.

The movement and future concentrations of contaminants are predicted. Methods of contaminant transport are discussed, relatively simple models and sensitivity analyses being preferred. Impacts on future water usage are assessed.

Two approaches to mitigation of aquifer contamination are considered. The first is groundwater protection using measures engineered to stop the spread of contaminants, and the second includes in-situ treatment, or removal, treatment and re-injection of treated water. The factors influencing the choice of these control alternatives are discussed. Risk assessment is made for the various remedial alternatives.

2.2.1.3 Review of Plans by the Nuclear Regulatory Commission (NRC)

Source document: "Standard Review Plan for UMTRCA, Title 1 Mill Tailings Remedial Action Plans", NRC Division of Waste Management, October 1985.

This document has been carefully tailored to correspond to the Technical Approach Document. Standard Review Plan (SRP) describes factors that NRC considers in approving the RAP. These factors are arranged under the same four headings as in the Technical Approach Document described above, namely:

- surface water hydrology and erosion protection,
- geotechnical stability,
- radon attenuation, and
- water resources protection.

Each technical section is treated in four sub-sections as follows:

- scope of the review,
- acceptance criteria,
- review procedures, and
- evaluation findings.

The technical content of this document is quite detailed but it will not be discussed any further here, since essentially it repeats the Technical Approach Document.

2.2.1.4 Surveillance and Maintenance by DOE

Source document: "Guidance for UMTRA Project Surveillance and Maintenance." UMTRA-DOE/AL-350124, Albuquerque, New Mexico, January 1986.

This is a guide to the inspection, monitoring and reporting to ensure that the inactive tailings piles are behaving in accordance with the remedial action plans.

The document details five activities:

- definition and characterization of final site conditions,
- site inspections,
- groundwater monitoring,
- aerial photography, and
- custodial maintenance and contingency repair.

Final site conditions are defined and characterized prior to the completion of remedial actions at a site. As-built drawings are compiled, a final topographic survey made, a vicinity map prepared, and ground and aerial photographs taken. Survey monuments, site markers, signs, and a network of monitoring wells are established.

Site inspections are of three types: Phase I, Phase II, and contingency inspections. Phase I inspections are scheduled regularly and are conducted to identify conditions that may affect design integrity. Phase II inspections depend upon potential problems identified during Phase I inspections. Contingency inspections occur when information has been received that indicates that site integrity is threatened by natural events, for example, a severe earthquake.

Monitoring of groundwater conditions may be necessary as part of the surveillance. Monitoring is conducted in two phases, detection monitoring and compliance monitoring. Detection monitoring is designed, for example, to detect changes in groundwater quality attributable to the tailings. If a significant change is apparent, compliance monitoring is initiated. Compliance monitoring is more extensive and quantifies rates and magnitudes.

Surveillances include the acquisition and interpretation of aerial photography. The main purpose of aerial photography is to aid inspectors in the field and to provide a permanent, visual record of site conditions. Colour infrared stereo photos, high oblique prints, and low oblique, natural colour photographs are taken at the completion of remedial action.

Custodial maintenance such as grass mowing or fence repair are required at some sites. Extreme natural events or purposeful intrusion may occur at a site and immediate contingency repair is undertaken. Compared with contingency repair, maintenance is less costly, smaller in scale, and more frequent in occurrence. Contingency repairs are very unlikely to be needed, but the costs may be substantial.

Inspection checklists help personnel to report in a methodical manner ensuring that items are not overlooked. Together with aerial photographs, field measurements, maps, etc. these are compiled in a site file.

The process of surveillance and maintenance is summarized in the flow chart reproduced in Figure 2.2.1-2.

2.2.1.5 Summary

The UMTRA project has been thought out very carefully in great detail. It involves a sequential procedure in fourteen key steps and activities from early site assessment through to certification and licensing. The generalized approach showing the timespan envisaged is reproduced in a flow chart in Figure 2.2.1-3. The remedial action activities associated with the UMTRA project sites are documented in a recently published site management manual (DOE 1986). This manual describes the project's objective, participants' roles and responsibilities, the technical approach for accomplishing the objective and the planning and managerial controls used in performing the site work.

Canada can gain considerably by studying the U.S. clean-up program. Both technical and procedural methods are of benefit. Caution should be exercised in selecting aspects which would be applicable and of benefit in Canada. Major portions of the 1978 UMTRA legislation have not been implemented due in part to jurisdictional disputes between EPA and NRC (Crawford 1985b). Other probable reasons for delay are believed to be unresolved. Litigation and political manoeuvring by environmentalists and industry. This suggests the need for a less cumbersome regulatory framework.

The basic different between the U.S. and Canadian approach to regulatory practices is that the U.S. has to follow the legal route, setting regulations and inviting adversarial dispute, whereas in Canada the responsible agencies choose to work in co-operation and negotiation with the mining companies, being content merely to set guidelines rather than regulations.

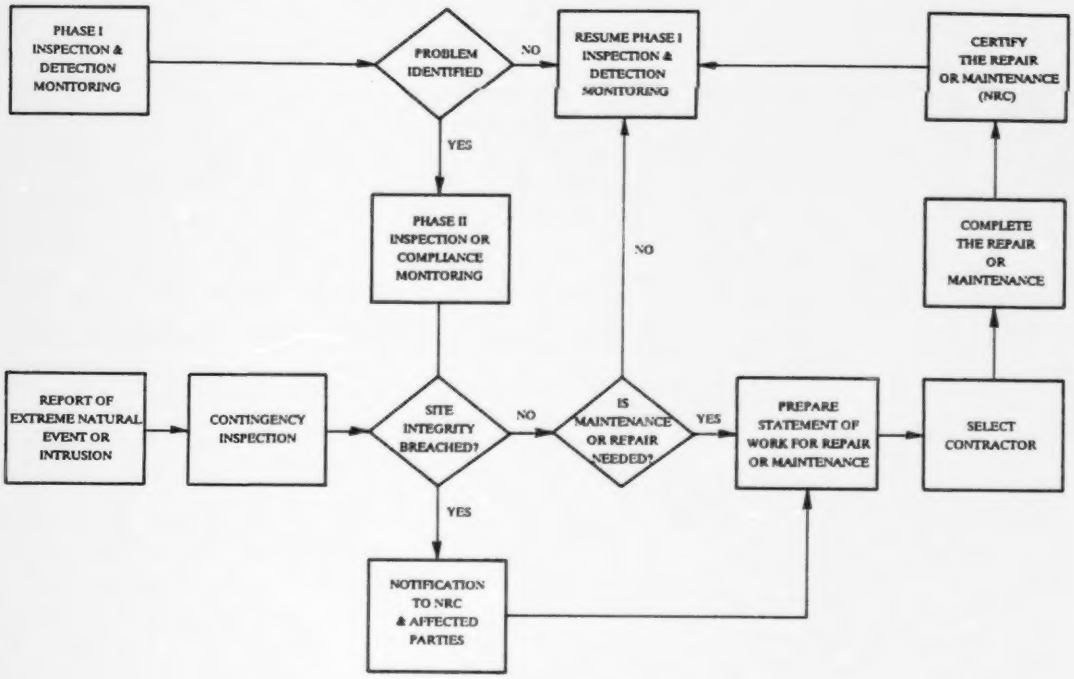

PHASE I INSPECTION & DETECTION MONITORING
PROBLEM IDENTIFIED
NO
YES
RESUME PHASE I INSPECTION & DETECTION MONITORING
CERTIFY THE REPAIR OR MAINTENANCE (NRC)
PHASE II INSPECTION OR COMPLIANCE MONITORING
NO
COMPLETE THE REPAIR OR MAINTENANCE
REPORT OF EXTREME NATURAL EVENT OR INTRUSION
CONTINGENCY INSPECTION
SITE INTEGRITY BREACHED?
NO
IS MAINTENANCE OR REPAIR NEEDED?
YES
PREPARE STATEMENT OF WORK FOR REPAIR OR MAINTENANCE
SELECT CONTRACTOR
YES
NOTIFICATION TO NRC & AFFECTED PARTIES

Figure 2.2.1-2 UMTRA Surveillance & Maintenance Process (after DOE 1986)

2.2.2 REGULATION OF NEW AND ACTIVE TAILINGS SITES BY NRC

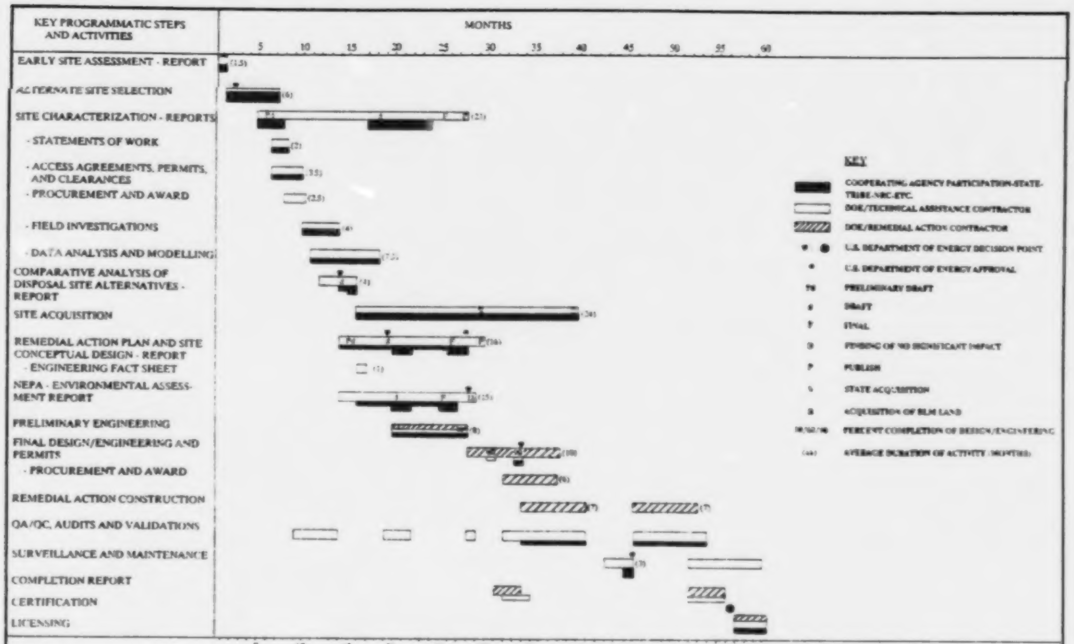
An NRC source material license is required to process or refine ores containing 0.05 percent by weight or more of uranium. By this means the NRC regulates the uranium industry in the interests of the health and safety of the public. Licenses are issued for 5-year periods. To obtain the license an applicant must provide information on the proposed facilities, equipment, experience and procedures. Part of the license application deals with effluent control and waste management systems. This is spelt out in NRC Regulatory Guide 3.5 - Standard Format and Content of License Applications for Uranium Mills.

Two different approaches are recognized:

- above-grade systems, and
- below-grade systems

Where dykes, levees and ponds prevent the release of liquid or solid wastes these are termed retention systems. The applicant is referred to Regulatory Guide 3.11 - Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills. This lists the information the regulator is looking for in the license application, such as on design, construction, inspection and maintenance.

Below-grade containment is thought of as the "prime option" for tailings disposal. It refers to placement in mines or specially excavated pits so that the need for construction of retention structures



NOTES

1. FUNDING PROBLEMS, UNFORESEEN GEOLOGIC AND CLIMATIC CONDITIONS AND PUBLIC INTEREST MAY SIGNIFICANTLY AFFECT THIS SCHEDULE.

2. CHART IS BASED ON THE PREPARATION OF AN ENVIRONMENTAL ASSESSMENT. ENVIRONMENTAL IMPACT STATEMENT PREPARATION WILL ADD SIX (6) MONTHS TO THE PROCESS AND DELAY SUBSEQUENT STEPS BY THAT AMOUNT.

3. REMEDIAL ACTION CONSTRUCTION WILL GENERALLY REQUIRE TWO (2) FULL CONSTRUCTION SEASONS. LARGER SITES MAY REQUIRE ADDITIONAL TIME.

4. BAR THICKNESS DENOTES RELATIVE DEGREE OF INVOLVEMENT IN THAT STEP OR ACTIVITY.

5. THE STEPS AND ACTIVITIES AND TIME REQUIRED ARE BASED ON CURRENT STATUTES, REGULATIONS, COOPERATIVE AGREEMENTS, POLICY AND PRACTICE, SPRING 1985

Figure 2.2.1-3 Generalized UMTRA Remedial Action Flow Chart (after DOE 1985)

is eliminated. The applicant for either a license renewal, or for a new license, must inform the regulator how to construct and operate the below-grade system. Below-grade disposal was used in a mined out pit at the Umeto property in Wyoming (Hoffman and Wong 1985). It is the first application of this system.

The applicant must provide an Environmental Report evaluating alternative sites and disposal methods in support of this tailings disposal system. Reference is made to Regulatory Guide 3.8 - Preparation of Environmental Reports for Uranium Mills. This spells out the information the regulator requires on such topics as proposed activities, the site, milling and tailing disposal, environmental effects, measurements and monitoring and so on.

The tailing management and reclamation program is required to address the following performance objectives that are called for in NRC 10 CFR 40:

- reduce direct gamma radiation from the impoundment area to essentially background,
- reduce the radon emanation rate from the impoundment area to less than 2 pCi/m^2s by placing sufficient earth cover, but not less than 3 meters, over the tailings,
- eliminate the need for an ongoing monitoring and maintenance program following successful reclamation, and

- provide surety arrangements to ensure that sufficient funds are available to complete the full reclamation plan.

The recent status of the industry in complying with current regulatory requirements for waste management at uranium mills is indicated by the following abstract (quoted in full) from a report by NRC (1985):

> "This study evaluates the degree to which surface impoundments at licensed facilities comply with significant changes in NRC requirements initiated by enactment of EPA's final environmental standards for uranium recovery facilities (40 CFR Part 192). Impoundment liner requirements, groundwater protection standards, ground-water monitoring and corrective action programs, and site closure standards are the most significant regulatory modifications.
>
> The compliance status of 30 conventional mills and 31 in-situ mines is determined from a review of Nuclear Regulatory Commission and agreement state docket files through November, 1983. Results of this review show that a majority of conventional uranium mill tailings management systems are deficient with respect to liner requirements for new impoundments or proposed expansions to existing impoundments, as well as with respect to some aspects of ground-water monitoring and compliance programs. Furthermore, the status of conventional mill site closure plans is highly uncertain at this time. Although surface impoundments at in-situ uranium mines also are deficient with respect to ground-water monitoring programs, they generally comply with other changes in requirements imposed by 40 CFR Part 192."

2.2.3 RESEARCH BY NRC

During the last decade a major program of research has been initiated by the NRC into the management of radioactive wastes. A large part of this program has been concerned with uranium mill tailings. Most of the research has been carried out under contract by institutions such as the Pacific Northwest Laboratory, and Oak Ridge National Laboratory. Reports on the findings are readily available through NRC, and they provide much valuable and useful information.

2.2.4 COMPARISON WITH CANADIAN PRACTICE

The most significant difference between the Canadian and U.S. reclamation practices is the absence of rigid or detailed standards and criteria for works in Canada. There are no laws or regulatory standards applying specifically to uranium tailings pile remedial work in Canada. Deposits prepared for abandonment are subject to the regulatory control of the Atomic Energy Control Board, which has issued broad guidelines. The Board reviews abandonment plans on a case by case basis. In reviewing plans, the Board also considers appropriate Provincial and Federal regulations.

The NUTP study (SRK 1986) approaches the rate of release of contamination from the piles (analogous to the EPA requirement of 20 pCi/m^2s) on the basis that if the rates of change of release of contaminants from the piles are very, very small, then the changes in the release rates may not be significant for a very long time. Small but perpetual change which results in cumulative increases in release rates may bring about unacceptable rates of release in lesser periods. Rapid changes could result in large releases in short periods.

The NUTP study (SRK 1986) does not, however, define such critical terms as "very, very small", "significant", "very long time", or "unacceptable release rates". Such decisions are left to the companies and the professionals advising the companies affecting remedial works, regulatory authorities, and to the normal process of public review.

Geographical differences between the two countries also play a major part as follows:

- because of the remoteness of many Canadian uranium mill tailings deposits and the typically higher soil moisture contents, radon emanation control is considered to be less critical. This reduces the perceived need for covers over tailings from low grade uranium deposits.

- in the areas of Canada susceptible to permafrost, frost heave and other frost effects may disrupt rigid covers. The use of flexible, self regenerating covers, such as those involving vegetation and water, have long-term advantages in controlling erosion.

- the Canadian long-term, stable cover, choice is forest vegetation. At most U.S. sites vegetation cannot be relied on in the long-term to provide a stable entity. In the U.S.A., rock covers are almost exclusively relied on to provide erosion protection. Conceivably Canada will adopt a reasonably effective cover of soil in which forests may establish as the ultimate cover. Water cover may also be a practical and acceptable cover in appropriate circumstances in Canada.

Ore types also differ in the two countries. In Canada potential contamination of surface waters can arise from the presence of appreciable amounts of nickel, arsenic and acid generating material in the tailings. Recently mined grades in Saskatchewan are up to 10 times higher than mined in the U.S.A.

Further comparison of the difference in approach in the two countries is given in Caldwell and Robertson (1987).

2.3 TRENDS ELSEWHERE

While the bulk of the recent technology research has been undertaken in the U.S.A., work has been done elsewhere, and a brief survey of approaches in other countries follows.

2.3.1 AUSTRALIA

The ownership of minerals in Australia is vested in the Crown and it is a State responsibility similar to the situation in Canada. The Minister for Mines and Energy for the State has regulatory authority, and the Department of Mines is the administrating agency.

Under the Environment Protection (Nuclear Codes) Act 1978 the Commonwealth Government produced the Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982).

2.3.1.1 Code of Practice and Guidelines

The Australian Government has issued Guidelines to the Code of Practice. The five guidelines germane to this manual are:

- development of a waste management program for a uranium mining/milling operation,

- design and operation of a water management system for a uranium mining and milling operation,

- tailings impoundment for uranium mines,

- waste rock and ore stockpile managements, and

- decommissioning and rehabilitation of uranium mine, mill and waste disposal sites

A number of concepts and uses of terms are basic to the Australian approach.

Storage means containment for an interim period prior to retrieval and ultimate disposal, while disposal itself implies no intention of future retrieval. For example temporary storage may be undertaken prior to in pit disposal on completion of mining. The desired waste management objective is disposal, and more importantly with no reliance on continued surveillance and maintenance to ensure integrity of the facility.

For the purpose of defining a specific area or space within which waste management takes place, a Restricted Release Zone (RRZ) is envisaged. The RRZ is defined as "an approved zone about and below a mine and/or mill from which release of radioactive material shall be minimized in accordance with the requirements of the appropriate authority". Thus the RRZ is a three dimensional zone operating to minimize the area being disturbed, but it also provides boundaries at which the company and the regulatory authority can determine if the objectives are being met. Releases from the RRZ are either prohibited or controlled.

Waste management systems should use "Best Practicable Technology", defined as that which from time to time is relevant to a specific project enabling wastes to be managed to minimize radiological risks and detriment to people and the environment. It must, however, take account of available technology, cost relative to the protection achieved, the adequacy of protection already being achieved, local site conditions and potential hazards of the wastes over the long-term.

Management is thought of in the operational period, during decommissioning and rehabilitation, and during the long-term. In designing the facility to meet long-term needs a distinction is made between design life and structural life. A clear statement of the distinction and the time periods envisaged is quoted below in full:

> "Design life" is the period for which the structure is expected, by the designer, to perform fully in accordance with the objectives of the design, such as rates of releases of contaminants, taking into account the known parameters and influences. The design life is a prediction of the useful life of the structure. A structure, once in service, will usually retain integrity of the materials and components used to build the structure for a period considerably longer than the design life. Such a structure will show signs of deterioration but will be capable of performing the functions of the design to a reduced extent. The "structural life" is therefore the actual measurement of the useful life of the structure in performance. The structural life may be extended by renovation and maintenance of the structure. In the context of this guideline the objective in the engineering of a waste management structure should be to attain a design life of at least 200 years (institutional controls such as record keeping, monitoring and land-use restrictions should operate as an adjunct to design criteria during this time) and a structural life of a substantially longer period, of the order of 200 to 1,000 years, taking into account estimates of geomorphic and climatic influences so as to minimize rates of contaminant release caused by denudation, seepage, and exhalation.

Radioactive wastes, and non-radioactive pollutants in the wastes, particularly heavy metals, are considered in the waste management program.

In considering water management systems or strategies the following categories are distinguished:

- Absolute No Release, (irrespective of whether water is treated or not),
- No Release (PMP designed for in storage pond capacities),
- Contingency No Release, (100 year storms designed for),
- Controlled Release, (water held until suitable conditions prevail, i.e., after treatment), and
- Uncontrolled Release (water managed only to the extent necessary for mining and milling purposes).

In Australia water management systems can be divided on a geographical basis into two groups as far as uranium mining is concerned:

- the arid regions, where there is little difficulty maintaining a no release system, and where there is more likely to be a concern for reliability of water supply for mining, and
- the northern monsoonal regions where there is only a slight excess of evaporation over rainfall making a no release system just possible, but where rainfall patterns such as sudden heavy rains have to be allowed for.

In the design of tailings impoundments particular emphasis is placed on site selection, and certain criteria must be met of which the following are worth comment:

- location must be away from population centres, and
- there should be no extraneous catchment area, and the site should not be subject to flooding.

These are very specific, concisely worded requirements. Although the first is reasonably achievable in the sparsely populated mining districts of Australia, just as in Canada, it does imply that growth of future populations centres should be restricted near to tailings impoundments, or alternatively tailings will require relocation at some time in the future which is in itself incompatible with their concept of disposal. The second requirement, if met, means that flood erosion will never be a concern for the future integrity of the impoundment.

The five impoundment types (IAEA 1981) are considered:

- valley dam impoundment,
- ring dyke impoundment,
- mine-pit impoundment,
- specially-dug pit impoundment, and
- underground mine impoundment.

Valley dam impoundments would seem to be virtually incompatible with the site selection criteria for no extraneous catchment area, although the Guidelines do not say so.

In general the Australian Guidelines on impoundment and control structures follow rather closely the current U.S. thinking, which is understandable since in general their geographical conditions resemble the arid Southwest.

Rehabilitation of waste disposal system structures "should maintain their integrity for a period in excess of 100 years"; details of techniques are discussed in the separate guidelines.

2.3.1.2 Typical Mines

The Mary Kathleen uranium mine is in Queensland about 50 km east of Mount Isa. About 11 million tonnes of tailings have been rehabilitated following closure of the mine in 1982. The climate is hot and dry, but storm showers are intense. The tailings are covered by 1 to 2 m of waste rock providing erosion protection. Evaporation is believed to take care of runoff (per. comm. Levins 1986). Any seepage is contained within the local catchment. Because of the alkaline nature of the local calcareous red earth soils, seepage is clarified to standards meeting local agricultural usage. One of the basic principles behind the rehabilitation was to make all areas safe for public access, (Ward et al 1984 and (Ward 1985).

Major mines in Australia are in the Northern Territory, the high-grade Nabarlek project, the Koongarra mine and the low-grade (0.3 to 0.4%) Ranger project. All are in the Alligator Rivers Region about 200 km east of Darwin. Ranger, with reserves in excess of 100,000 tonnes, was commissioned in 1981. The climate is hot, wet-dry tropical monsoon type. Tailings management is by the Saturated System (sub-aqueous) using a square ring dyke impoundment and a grouted cut-off trench designed to meet a no release of contaminants objective. Subject to review after 1989 the ultimate disposal location of the tailings is supposed to be below-grade in the mined-out pits. There are various options for rehabilitation of the tailings as presently stored behind the dams, (Haylen 1984), however consolidation of the tails below water, and thus its impact on settlement of the random cover, are a concern. Prior to start-up the project was subject to long-protracted inquiries and negotiations revolving around Aboriginal wishes and the impact on a National Park, which surrounds it. Water management to maintain a No Release system, in these northern Australian mines is considered (Burgess 1980).

2.3.2 FRANCE

The French take a far more pragmatic approach to uranium tailings disposal. France has a greater percentage of electricity is generated from nuclear power (75% currently) than in any other country in the world. This is a dramatic rise from 7% in 1974 at the time of the oil crisis. However, France is the only country in western Europe with substantial resources of uranium. This fact together with the significant lack of major alternative power resources, such as coal, gas, oil or hydro-electrical sites, explains their reliance on nuclear fuel.

Mining and extraction of uranium in France has been undertaken since about 1950. Total domestic uranium supply is roughly 3,250 tonnes/yr, (EMJ 1986).

Currently uranium milling operations in France consist of three mills operated by SIMO of the COGEMA Group (Compagnie Generale des Matieres Nucleaires), one mill operated by MOKTA, a Cogema affiliate, and two mills operated by TOTAL Compagnie Miniere. Waste management practices vary with each operation, hence a brief description of the methodology used at each site can provide general information on uranium tailings management in France.

2.3.2.1 Cogema Group

a) Bessines Plant

This plant is the largest of the operations with a process capacity of about 1 million tonnes/yr capable of producing about 1500 tonnes/yr of uranium concentrate. It is about 35 km north of Limoges in the Limousin mining district in central France. Milling operations at the Bessines mill began in 1960. Ore mined from granitic rocks is provided from both open-pit and underground satellite mines in the area within a 20 km radius of the plant. The mill circuit is an acid leaching circuit with belt filtration for recovery of pregnant solution.

The washed, filtered leach residue is re-pulped and neutralized with lime prior to pumping to a backfill plant. Cyclone underflow is used as backfill in the underground mines and the cyclone overflow is discharged to the tailings area.

Tailings containment at the Bessines site was within the Lavaugrasse Pond until 1978. This pond was constructed using engineered embankment dams with cyclone sands used for the dam faces. Since 1978 the neutralized tailings slurry has been discharged to the mined-out Brugeaud pit along with minewater from a small adjacent underground mine. The capacity of this pit has been extended by construction of a dam on the south-east side of the pit. Pressure filtration of tailings and trucking to small open pits at nearby satellite mines is being contemplated for future containment of tailings at Bessines.

The supernatant water in the Brugeaud tailings pit is recycled to the mill process and any excess is treated with barium chloride for radium removal. The treated effluent is clarified in the old Lavaugrasse tailings pond and discharged to the local watershed.

b) Lodeve Plant

The Lodeve site, in Southern France, is a new operation started in 1981 at a production rate of 1,000 tonnes of uranium per year.

Herault mines supply the Lodeve concentrator. The original source of the uranium was the granites of the Massif Central and in volcanism, but groundwater transported it to overlying Permean sediments where it was discovered as precipitates in outcrops. Current reserves are approximately 20,000 tonnes with an ore grade of 0.2%. Initial mining was by open-pit but now all the ore production is from underground.

The ore is high in carbonate content (6-10% CO_2) hence a two-stage alkali leaching circuit is used with belt filtration for recovering pregnant solution. Precipitation of uranium by lime is followed by roasting and re-dissolution with sulphuric acid, and yellowcake precipitation with magnesia.

Waste treatment circuits within the mill operation include recovery of molybdenum from the barren solution by precipitation with sodium hydrogen sulphide; removal of organic contaminants and traces of molybdenum by adsorption on activated carbon; removal of trace uranium (20-40 mg/L) by precipitation with sodium carbonate at pH 8.5; and removal of sodium sulphate by crystallization. The remaining condensate is recycled to the mill process.

Minewater is used as process water and water recycle from a holding pond is practiced. A barium chloride treatment station treats mill water for radium and uranium removal. Water discharge to the local watershed is approximately 85 m^3/h containing less than 0.37 Bq/L Ra-226(diss.) and less than 1.8 mg/L uranium.

The leach residue contains little soluble contamination due to the high wash efficiencies in the belt filtration circuit. The washed, dewatered, belt filter cake is therefore discharged via conveyors directly to one of two mined-out open pits which make up the tailings containment area.

c) L'Ecapiere Plant

L'Ecapiere mill located near the Loire River in western France commenced operations in 1958. Current ore production is from both underground and open pit mines. The mill tailings slurry is pumped at 25% solids to cyclones at the tailings containment pond. The dams are constructed of cyclone sands with the slimes discharged within the pond area. A portion of the cyclone underflow is also used as backfill in the underground mines.

Tailings water is reclaimed via decant towers and barge pumps to a secondary holding pond where the water is neutralized and treated for radium removal prior to discharge to the local watershed.

2.3.2.2 Mokta

Langogne Plant

The Langogne mill in central France has been in operation since the early 1960's. It is a smaller open-pit mine using heap leaching for uranium recovery. The ore is placed in plastic-lined leach piles contoured to resemble the local landscape. The ore piles are compacted and fitted with solution injection pipes during construction. A clay cap is placed over the ore and leaching is achieved by pumping lixiviant through the injection pipes.

2.3.2.3 Total

Dong-Trieu Plant

The Dong-Trieu mill located in central France started operations in the late 1970's. Ore is mined both from an open-pit and from underground. An acid leach circuit is used in the mill. Washed leach residue is dewatered with belt filters and discharged via conveyors and trucks to dyked areas and excavated pits for tailings disposal.

2.3.2.4 Philosophy of Tailings Management in France

At the present time there are about 18 million tonnes of uranium tailings in France (Farges et al 1986). They suggest the possibility of controlled releases to the environment as a disposal alternative to confinement. They envisage a dispersion and dilution strategy, rather than perpetual storage concentrated at a particular location. True dispersion would comprise discharge to major rivers or wind dispersion in a desert. Confinement of sedimented tailings either in deep lakes or after dumping into the sea is also envisaged.

Dumping in rivers or at sea is virtually an unconfined non-retrievable strategy. Research of the Commissariat a l'Engerie Atomique is looking into these possibilities, as well as re-use and disposal.

The following observation, (Pradel and Zettwoog 1986) freely translated is noteworthy:

> "To assess all factors (that enter the decision making process), particularly exposure levels to the population, it is fashionable at present to rely on mathematical models of geological and ecological pathways. In our opinion it is a mistake on the part of both computer specialists and environmental scientists to believe that such models can accurately predict real field conditions. The rush to produce increasingly sophisticated models doesn't solve the problem nor increase confidence in predictions, but it does increase costs. We therefore have abandoned these attempts, which seem to produce little more than thick reports."

It is noted that there is a greater usage of tailings dewatering techniques (primarily using vacuum belt filters) and placement of dewatered tailings in pits or retainment dykes in France. This may be a consequence of higher precipitation conditions in the west of Franch than is typical of the U.S. and Australian mining areas, as well as the proximity to more densely populated areas. Under these circumstances, the additional costs of tailings dewatering and mechanical placement of the tailings may be set against the environmental requirements.

It is also apparent, that the use of tailings sands for embankment construction is still accepted practice, whereas it is no longer considered acceptable in Canada and the U.S.A.

2.3.2.5 Regulations for Uranium Mining in France

All mining activities in France, including eventual closures and decommissioning of sites, are regulated by the "Code Minier" which provides for the rights and obligations of the owner or operator of uranium mining and milling facilities. All regulatory aspects rest purely with local administration districts who have complete control over uranium mining owners and operators.

New uranium mines or new uranium milling facilities are required by law to prepare an environmental impact statement which is presented to the local administrative district to obtain mining permits. For mines opened after 1977 this impact study must include decommissioning and close-out plans. Mines that began operation prior to 1977 must inform the administrative authority when a decision to close has been taken, and they must then submit their related decommissioning plan.

The applicant has to justify his technical and financial ability to undertake and run the proposed operations before getting permission to operate or mine a deposit. The owner/operator of a uranium mining project is financially responsible for the decommissioning plan presented to the local authority. Furthermore the local administrative district has the power to contract at the owner/operator's expense any remedial work deemed necessary for the protection of the employees, the public or the environment. Establishing decommissioning costs is at the discretion of the mine operator and the management of necessary funds for decommissioning is the operator's responsibility.

Effluent guidelines are set by the local administrative district based on recommendations from central government agencies such as:

- Ministry of Industry and Research,
- Ministry of Environment, Department of Pollution Prevention,
- Ministry of Agriculture,
- Ministry of Health and Welfare, and
- Water Management Agencies responsible for the management of rivers.

In setting effluent guidelines the characteristics of the receiving watershed are taken into account, such as upstream and downstream water quality, the existing salinity of the water, and the total cation and anion content. Actual regulatory levels differ from one uranium mining area to the next.

All regulations for uranium mines are coordinated through a single central government department, the Ministry of Industry and Research who have regional offices to assist the local administration district in the control of the regulations. Radiation protection is provided by the Institute of Nuclear Safety and Protection of the Atomic Energy Commission, who have the responsibility for radiation protection at operating facilities. They provide the operator with radiation results and advise on necessary remedial action.

2.3.3 SOUTHERN AFRICA

The Rossing uranium mine in Namibia (South West Africa) produces about 40,000 tonnes of tailings daily, and is probably the largest uranium mine in the world. It is also unusual in so far as the uranium occurs in a granitic host rock, whereas most ores occur in sedimentary formations. At initial start-up in 1976 tailings deposition was from behind a starter dam, which also acts as the toe filter for the main valley dam. Alternative methods of deposition are a) from the upstream end of the watershed in the form of a cone, and b) the ring method from three sides of the pond (Hendry and Wright 1985). These alternatives minimize dam building and environmental impact.

In the Republic of South Africa uranium is produced almost exclusively as a byproduct of gold mining. The total volume of gold/uranium tailings that has accumulated in impoundments on the surface is approximately 2.3 billion tons over approximately 7500 ha. (Best 1987). Current tailings production rates are approximately 102 million tons per year. South Africa is the second largest producer of uranium in the western world and continued production is assured by its association with the expanding gold mining industry.

These low grade but high volume ores are mined mainly in the Witwatersrand/Free State mining complex area which is densely populated. The topography is flat to gently rolling and the climate mild (hot summers and cool winters with some frost) with a considerable excess of evaporation over precipitation. The ores mined are pebble conglomerates vary similar to those mined at Elliot Lake and yield a tailings with essentially similar characteristics. The tailings are acid generating.

2.3.3.1 Tailings Management Practices in South Africa

The long history (over 100 years) of extensive mining in close proximity to the public and in an area of fairly uniform topographical, foundation and climatic conditions has resulted in the development of traditional, tried and tested, low cost methods of impoundment construction. The traditional method is variously termed the "irrigation", "day wall, night wall" or "paddock" method. The methods of dam construction are described in Robertson et al 1978, Blight and Steffen 1979, Gowan and Williamson 1987, and Gowan 1987.

The paddock construction method comprises an outer wall of perimeter paddocks, constructed by upstream methods, into which tailings are discharged during the day, and an inner basin into which tailings are discharged during the night. Tailings placed by irrigation techniques in the day wall paddocks are allowed to settle, the surplus water is decanted and the tailings are allowed to dry for a period to consolidate the tailings and achieve partially saturated conditions in the day wall. Partially saturated conditions are maintained in the day wall by the use of underdrains and minimizing the amount of water stored in the central basin or night paddock. To minimize water storage, use is made of a separate "water return dam" to which water is decanted. The stability of the day wall depends on the combination of evaporative drying, underdrainage and water storage minimization as well as close supervision of the irrigation placement. The rates of rise of the embankments are limited by the settling and evaporation rates that can be achieved. Typically, rates of rise are less than 2 meters per year (Wates et al 1987).

Because of the cost effectiveness of the system it has been extensively studied in recent years to define design techniques. Over the past 10 years it has become increasingly more profitable to reprocess many of the old tailings deposits to remove residual gold and uranium, and pyrite as sulphuric acid. This has resulted in the implementation of large reprocessing schemes involving removal and relocation of tailings at high tonnage rates. To cope with the increased tonnages and rates of rise of tailings impoundments, new methods of tailings construction are being actively investigated. Much of the resulting technology has been published in Wates and Brink 1987.

2.3.3.2 Reclamation and Environment Impact Control

The primary impacts of concern in South Africa have been the dusting from the tailings impoundments and the effects of contaminated surface water runoff on adjacent water quality.

To date reclamation has focussed on the control of these potential impacts, though the concern for groundwater protection is increasing. A considerable amount of effort and research has therefore been devoted to the establishment of vegetation directly on these acid generating tailings. Because of climatic differences, these studies are of limited value to Canada.

Since the tailings are acid generating the surface runoff is of low pH with high dissolved metals contents. Discharge of these surface waters is controlled by the construction of paddocks on the top of the tailings impoundments and along the toes of the embankments. They are sized to contain all water falling onto the tailings impoundment or running off from the sides and to store this until it evaporates. The paddocks also serve to retain solids eroded from the embankments. This latter function is particularly important since the revegetation of the impoundment sides has been found to be only partially successful in controlling erosion and large volumes of tailings are eroded and trapped in the toe paddocks annually.

The Chamber of Mines of South Africa has played a central role in the development of reclamation methods and have issued guidelines for the design, operation and closure of metalliferous and coal residue deposits (Chamber of Mines of South Africa, 1983).

2.3.3.3 Regulations for Uranium Tailings Disposal in South Africa

Currently, gold/uranium tailings impoundment construction and operation is controlled primarily under various parts of the Mines and Works Act, Water Act, Atmospheric Pollution Prevention Act, Nuclear Energy Act, Environmental Conservation Act and the Private Act on Rand Water Board Statues which controls water quality in the Witwatersrand area. An amendment to the Environmental

Conservation Act is pending which will provide for more direct and coordinated control. A summary of the legislation controlling mine tailings in South Africa is available (Best 1987).

CHAPTER 3.0
CANADIAN DEPOSITS AND TECHNOLOGY

Conditions and concerns typical of Canadian sites at which uranium mill tailings occur, but which are not typical at sites in other countries, are:

- acid generating ores,
- very high grade nickel/arsenic clay ores,
- climatic conditions; particularly very low temperatures,
- environmental conditions, particularly abundant, high-quality surface waters with low contaminant buffering capacity, and
- limited land use and low population density.

Uranium waste disposal technology is well developed, both in Canada and in other uranium producing countries. Application of technology developed outside Canada to Canadian projects is appropriate and beneficial where it is suitable, or where it may be adapted, for Canadian conditions. These differences require diverse technology to optimize long-term waste containment. An understanding of Canadian site conditions is a prerequisite to the selection of the appropriate technology selection or development.

This chapter describes the Canadian uranium mining industry, reviews the effects of tailings, mine waste and site characteristics on appropriate technology. Three typical Canadian mine and mill developments and their environmental setting are described.

3.1 CANADIAN URANIUM MINING INDUSTRY

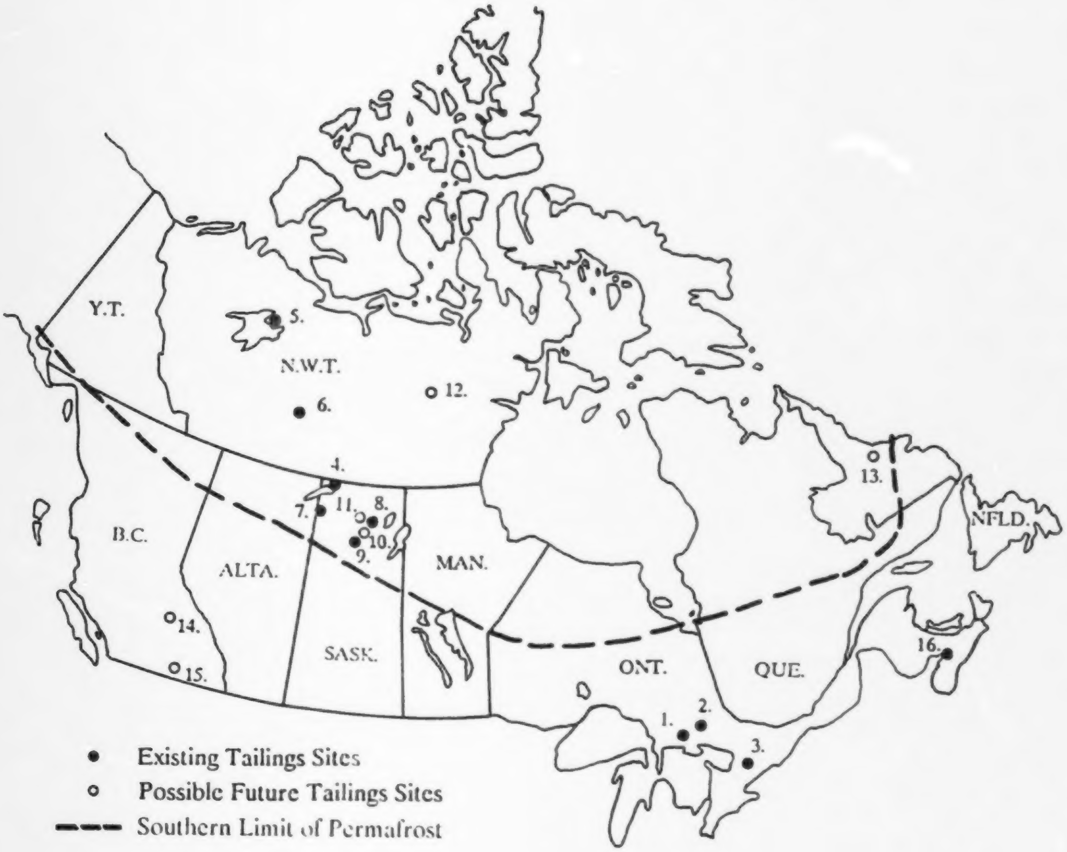
3.1.1 HISTORICAL OVERVIEW

Uranium mining in Canada started in 1942 with uranium recovery by acid leaching at the Port Radium mine in the Northwest Territories. Development in the 1950's led to the beginning of uranium production in the Beaverlodge area of northern Saskatchewan in 1953, development of numerous mines from 1955 to 1958 in the Elliot Lake area of northern Ontario, (Hester 1984), and in the Bancroft area in south-eastern Ontario.

In 1975 development began in northern Saskatchewan at the Rabbit Lake operation. This was followed by start-up of the Cluff Lake operation in early 1981, and the Key Lake operation in late 1983. The Collins Bay B-Zone deposit was started in 1985 at Rabbit Lake. By 1986 Saskatchewan was producing 60 percent of Canada's uranium.

Saskatchewan will continue to play an important role in uranium production in Canada with other high-grade deposits, especially the Cigar Lake property and Eagle Point, awaiting development in the 1990's and in years to come. In addition to the high-grade Saskatchewan deposits, potential uranium producing areas in Canada exist in the Northwest Territories, British Columbia, Newfoundland and Nova Scotia. The Baker Lake area of the Northwest Territories holds some promise but uranium prospects in the latter three provinces have political as well as economic hurdles to overcome.

Canada is now the world's largest uranium producer. The location of past, current and future planned uranium producers in Canada, as well as other potential areas, are shown in Figure 3.1-1. The concentration of uranium production in two main areas of Canada, Ontario and northern Saskatchewan, is evident from this location map. The main uranium producing properties, both active


Y.T.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
NFLD.
1.
2.
3.
4.
5.
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8.
9.
10.
11.
12.
13.
14.
15.
16.
● Existing Tailings Sites
○ Possible Future Tailings Sites
Southern Limit of Permafrost

1. Elliot Lake
2. Agnew Lake
3. Bancroft
4. Beaverlodge, Lorado, Gunnar
5. Port Radium
6. Rayrock
7. Cluff Lake
8. Rabbit Lake/Collins Bay
9. Key Lake
10. Cigar Lake
11. Midwest, Dawn, McClean
12. **Baker Lake (Kiggibik - Lone Gull)**
13. Michelin/Kitts
14. Rexpar
15. Blizzard
16. **Millet Brook**

Figure 3.1-1 Location of Uranium Deposits and Mining Areas in Canada

and inactive, in northern Saskatchewan and at Elliot Lake, Ontario are shown on Figures 3.1-2 and 3.1-3, respectively.

3.1.2 INACTIVE SITES

3.1.2.1 General

Table 3.1.2-1 summarize conditions at inactive tailings sites in Canada. The list includes the inactive mines in the Northwest Territories, Saskatchewan, Ontario (Bancroft) and Ontario (Elliot Lake area), together with period when tailings were deposited, the ore grade and total tonnage.

3.1.2.2 Northwest Territories

The two inactive sites in the Northwest Territories are Port Radium and Rayrock.

Port Radium

The abandoned Port Radium mine is on the shore of Echo Bay in McTavish Arm on the east shore of Great Bear Lake approximately 400 km northwest of Yellowknife. The property was discovered in 1930 by Gilbert A. Labine who found cobalt, silver and pitchblende in the area. Eldorado Gold Mines Ltd. began operating of a small radium-silver mine in 1933, and continued operation until June 1940 by which time 115,000 tonnes of ore had been processed.

The mine resumed production in 1942 as a uranium mine under the Canadian crown corporation, Eldorado Mining and Refining Ltd., and continued operation until 1960 by which time 6,808 tonnes of uranium (U_3O_8) had been produced. Subsequently Echo Bay Mines Limited re-activated the property and operated the mine as a silver-copper operation from 1976 to 1982, (Brown and Caine 1986).

During the radium-silver operating years (1933-1940) tailings from the gravity recovery circuit were discharged to the Cobalt channel in Great Bear Lake. Uranium recovery by acid leaching was initiated in 1942. As part of this operation, tailings in the Cobalt Channel were reprocessed for uranium recovery and subsequently discharged into small lakes on the peninsula and into Murphy Bay. Site measurements have shown that the existing tailings at this site were acid generating, (Kalin 1983a).

Rayrock

The abandoned Rayrock mine is in the Marian River area, approximately 150 km northwest of Yellowknife. The mine was operated by Rayrock Mines Ltd. from 1957 to 1959. It produced 208 tonnes of uranium (U_3O_8), (Brown and Caine 1986) and generated approximately 80,000 tonnes of tailings which were deposited in two separate drainage systems, a swampy area near Sherman Lake and a smaller area approximately 500 m away, (Kalin 1983b).

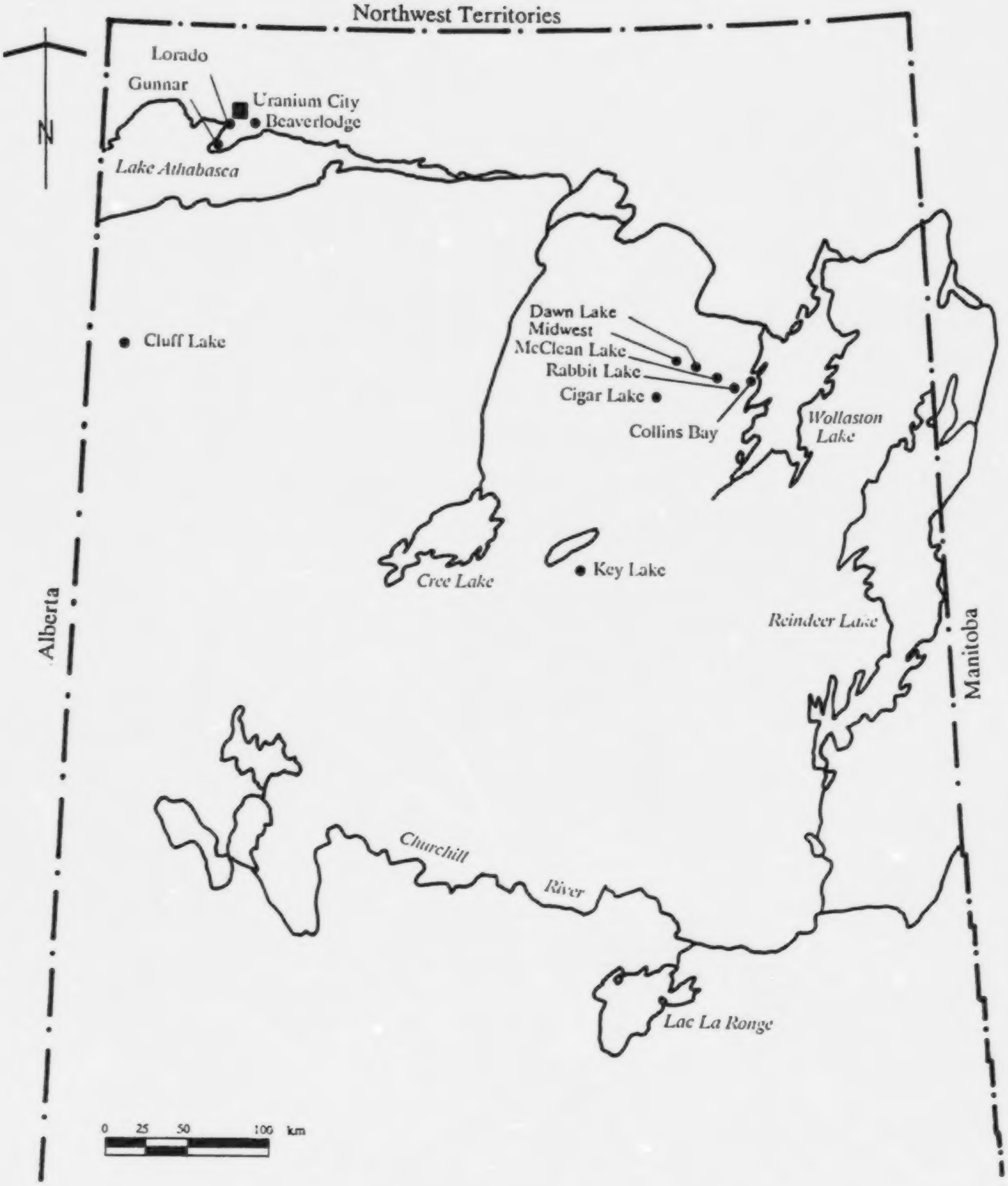

Northwest Territories
N
Lorado
Gunnar
Uranium City
Beaverlodge
Lake Athabasca
Cluff Lake
Dawn Lake
Midwest
McClean Lake
Rabbit Lake
Cigar Lake
Collins Bay
Wollaston Lake
Cree Lake
Key Lake
Reindeer Lake
Alberta
Manitoba
Churchill River
Lac La Ronge
0 25 50 100 km

Figure 3.1-2 Northern Saskatchewan Uranium Tailings Areas

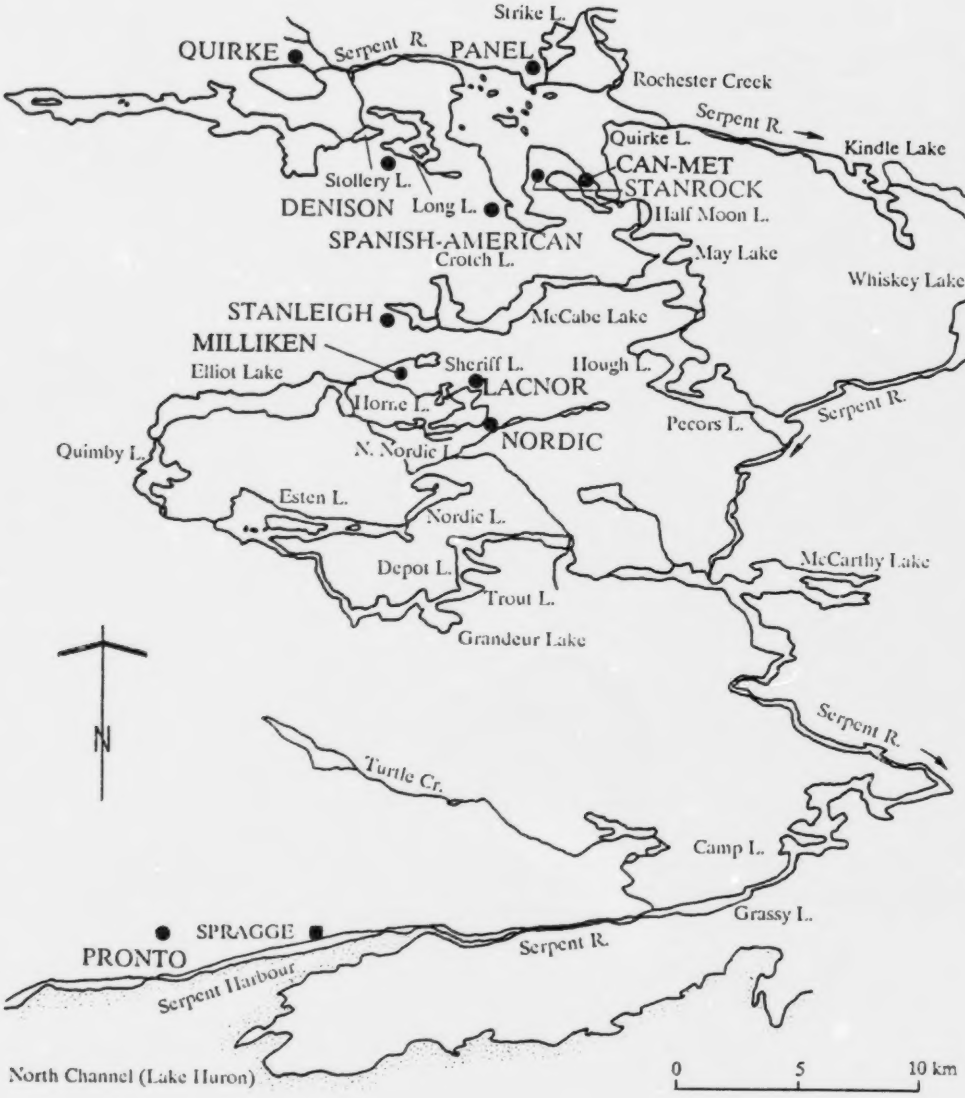

Strike L.
QUIRKE
Serpent R.
PANEL
Rochester Creek
Serpent R.
Quirke L.
Kindle Lake
Stollery L.
CAN-MET
STANROCK
DENISON
Long L.
Half Moon L.
SPANISH-AMERICAN
Crotch L.
May Lake
Whiskey Lake
STANLEIGH
McCabe Lake
MILLIKEN
Sheriff L.
Hough L.
Elliot Lake
LACNOR
Horne L.
Serpent R.
NORDIC
Pecors L.
N. Nordic L.
Quimby L.
Esten L.
Nordic L.
McCarthy Lake
Depot L.
Trout L.
Grandeur Lake
N
Serpent R.
Turtle Cr.
Camp L.
Grassy L.
SPRAGGE
PRONTO
Serpent R.
Serpent Harbour
North Channel (Lake Huron)
0
5
10 km

Figure 3.1-3 Ontario-Elliot Lake Uranium Tailings Areas

TABLE 3.1.2-1
INACTIVE CANADIAN TAILINGS SITES*

Site	Period of Deposition	Ore Grade ($\%U_3O_8$)	Total Tonnes Deposited (10^6 tonnes)	Area (ha)
Northwest Territories				
Port Radium	1933-1960	0.75(est)	0.91	unknown
Rayrock	1957-1959	0.25(est)	0.08	unknown
Saskatchewan				
Lorado	1957-1960	0.24	0.55	14
Gunnar	1955-1964	0.175	4.4(1)	75
Beaverlodge	1953-1982	0.20	6(2)	
Ontario (Bancroft Area)				
Dyno	1958-1960	0.1	0.36	3
Bicroft	1958-1963	0.1	2	8
Faraday	1957-1962	0.1	1.8	16
Madawaska	1976-1982	0.1	2	13(est)
Ontario (Elliot Lake Area)				
Nordic	1957-1968	0.1	12	85
Lacnor	1957-1960	0.1	2.7	25
Stanrock/Can-Met	1957-1964	0.1	7.5	61
Spanish American	1958-1959	0.1	0.45	10
Pronto	1955-1960	0.1	2.1	47
Agnew Lake(3)	1977-1983	0.1		
		Total =	42.85	

1. A total of slightly more than 5 million tonnes of ore were processed at the Gunnar Property with approximately 0.6 to 1.0 million tonnes used as backfill underground.

2. Approximately 10 million tonnes of tailings were produced in the Beaverlodge operation with 4 to 4.5 million tonnes being used as backfill underground.

3. Tailings from the Agnew Lake operation consisted of approximately 400,000 m^3 of waste precipitate sludge and 2 million tonnes of leached ore from heap leaching operations on surface.

*(adapted from SRK 1986; Melis 1983; BBT Geotechnical Consultants Ltd. 1986; Golder Associates 1986)

3.1.2.3 Saskatchewan

The three inactive uranium tailings sites in northern Saskatchewan are located on the north side of Lake Athabasca approximately 50 km south of the Northwest Territories border.

Lorado

The Lorado tailings site is approximately 10 km southwest of Uranium City on the west shore of Nero Lake. An uranium mill was operated from 1957 to 1960 by Lorado Uranium Mines Ltd. using an acid leach circuit, ion exchange with sodium chloride elution and magnesium diuranate precipitation.

550,000 tonnes of tailings were deposited at pH 2 directly into Nero Lake. The tailings at this site are pyritic and acid generating due to the high sulphide content (15%) of the Lorado ore, (Kalin 1982). Gangue minerals in the ore contains feldspar, quartz, pyrite, calcite and hematite. Uranium mineralization was pitchblende and yellow oxides, (SRK 1986).

Gunnar

The Gunnar property is 25 km southwest of Uranium City on the north shore of Lake Athabasca. A conventional acid leach, ion exchange and magnesium diuranate precipitation circuit was operated from 1955 to 1964. The Gunnar ore was made up of pitchblende and uranophane in a syenite containing about 8% calcite and 2 to 3% hematite, (SRK 1986).

Unneutralized tailings were deposited into Mudford Lake which is now referred to as the Gunnar Main Tailings. The Mudford Lake basin eventually filled and the mill tailings flowed north through two small lakes and into Langley Bay of Lake Athabasca. In September 1960 a mine backfill plant commenced operation. Approximately 40% of the tailings were used as backfill until the mine closed in 1964. 4.4 million tonnes of tailings were deposited on surface and approximately 0.6 to 1 million tonnes were used as backfill underground, (BBT Geotechnical Consultants et al. 1986). The tailings are not acid generating. At the Gunnar mine the abandoned open-pit has been flooded. A waste rock pile contributes contaminated seepage to Lake Athabasca, (Swanson and Abougendia 1981).

Beaverlodge

The Beaverlodge operation of Eldorado Nuclear Limited, on the north shore of Beaverlodge Lake in northern Saskatchewan, ceased production in June 1982 after 30 years of operation. Mill feed for the metallurgical complex originated from the Fay-Verna Mine, the Dubyna Mine and many other satellite mines in the area, (Eldorado Nuclear 1982).

The mill circuit, with a capacity of 1,650 tonnes per day, consisted of acid leaching of a pyrite flotation concentrate and alkali leaching of the flotation tails. Final yellowcake precipitation was with caustic soda. Approximately 4 to 4.5 million tonnes of coarse tailings were used as mine backfill and 6 million tonnes of tailings slimes were deposited in nearby lakes, (SRK 1986). Tailings decant water and mine water were treated with barium chloride and flocculant for radium removal, waste precipitates were retained in settling ponds and treated effluent was discharged into Beaverlodge Lake, see photos 3.1-1 and 2.

3.1.2.4 Ontario

In Ontario there are four inactive tailing sites in the Bancroft area and six in the Elliot Lake area.

Bancroft Area

Dyno

The Dyno mill was operated by Canadian Dyno Mines from 1958 to 1960 with approximately 360,000 tonnes of tailings being discharged into Farrell Lake. A rock dam separates the tailings from the main lake. Indigenous vegetation and the neutral pH of the water in the vicinity indicate that ecological processes provide natural reclamation of these tailings and other tailings in the area, (Kalin 1983b).

Bicroft

The Bicroft tailings sites occur at three distinct tailings areas; Auger Lake, Bicroft Proper and Bicroft Swamp. The mill, operated by Bicroft Uranium Mines, used an acid leach process and discharged

Photo 3.1-1 Lake disposal of tailings at Beaverlodge, Saskatchewan.

Photo 3.1-2 Discharge of tailings in the lake at Beaverlodge, Saskatchewan.

approximately 2 million tonnes of neutralized tailings from 1958 to 1963. These sites are reclaimed by the natural development of wetlands (Kalin 1983b).

Faraday/Madawaska

The Faraday Mine was operated by Faraday Uranium Mines Ltd. from 1957 to 1964 with 1.8 million tonnes of tailings deposited in a swampy area near Bentley Lake. The tailings were covered with overburden, seeded and fertilized to provide a good cover of indigenous vegetation, (Melis 1983).

In 1976 the operation was re-activated by Madawaska Mines Ltd. and uranium production continued until June 1982. The milling process included an acid-leach circuit, ion exchange and magnesium precipitation of yellowcake. Approximately 2 million tonnes of neutralized tailings were deposited into a new tailings site east of the mill. Tailings decant water was recycled to the mill. Any surplus water was treated with barium chloride and discharged through a settling pond and gravel bed (Melis 1983).

Elliot Lake Area

The tailings sites in the Elliot Lake area are the Nordic, Lacnor, Stanrock and Spanish-American sites in the vicinity of the town of Elliot Lake, the Pronto site on the north side of Highway 17 between Spragge and Algoma Mills and the Agnew Lake site north of Nairn Centre near Espanola. The Elliot Lake ore zone occurs within a uraniferous pyritic quartz-pebble conglomerate with uranium-bearing minerals including brannerite, uraninite and minor amounts of monazite and uranothorite, (SRK 1986).

Nordic

The Nordic mine, 6 km south of the town of Elliot Lake, was operated by Rio Algom from 1957 to 1968. Approximately 12 million tonnes of tailings were discharged into the tailings area, which is contained by rockfill dams on three sides and a rock hill on the north side. The mill circuit consisted of acid leaching, ion exchange and ammonia precipitation, the typical uranium circuit operated in the Elliot Lake area.

Due to its accessibility this tailings area has been used for numerous investigations. The entire tailings area was revegetated by Rio Algom Limited between 1971 and 1978. The tailings, like all tailings in the Elliot Lake area, are acid-generating hence seepage and runoff is collected and treated with lime and barium chloride for neutralization and radium removal. North Nordic Lake is used as a settling pond for the waste sludge, (Melis 1983).

Lacnor

The Lacnor Mine, located 5 km east from the town of Elliot Lake was operated by Northspan Uranium Mines Limited from January 1957 to July 1960 with 2.7 million tonnes of neutralized tailings discharged to a small lake. Ore from this mine came from the Lacnor Mine and the Buckles Mine. The seepage and runoff from this tailings area is directed by gravity to the Nordic tailings area, hence contaminated water from the site is treated in the Nordic treatment facility, (Golder Associates 1986).

Stanrock/Can-Met

The Stanrock tailings site, 12 km east of Highway 108, north of Elliot Lake, was used for tailings storage by Can-Met Exploration Ltd for their Can-Met mine and mill operation from 1957 to 1960 and by Stanrock Uranium Mines Ltd. from 1958 to 1964. 7.5 million tonnes of tailings were discharged into the tailings area with approximately 2.2 million tonnes coming from the Can-Met operation, (Melis 1983).

The Stanrock operation continued to recover uranium with an underground bacterial leach operation from 1964 to 1969. Denison Mines briefly re-activated mining in the late 1970's. Mine dewatering and recovery of uranium from minewater by precipitation with lime was carried out from 1977 to 1979. The neutralized minewater was discharged to the tailings area and the precipitate was trucked to the Denison mill for uranium recovery. In 1980 some mining of the Stanrock ore took place with trucking of the ore to the Denison mill for processing, (Reddy 1986).

Seepage and runoff from the tailings site is still being collected and treated with lime/caustic and barium chloride. Waste precipitates are collected in a small lake which acts as a settling pond.

Spanish-American

The Spanish-American mill was operated for a brief period by the Northspan Group in 1958 and 1959. A total of 450,000 tonnes of neutralized tailings were discharged into Olive Lake. Seepage and runoff from this area flows by gravity to Denison Mines' Long Lake tailings basin where it is treated with their tailings seepage and runoff.

Pronto

The Pronto mine, near Spragge Ontario, was operated by Pronto Uranium Mines Ltd. from 1955 to 1960, 2.1 million tonnes of tailings were produced. The majority of the tailing were copper tailings produced during the operation of the mill for copper recovery. Acidic surface runoff from this tailings site was treated with lime and barium chloride.

Agnew Lake

The Agnew Lake mine near Espanola was operated from 1977 to 1983 by Agnew Lake Mines Ltd. as an underground bacterial leaching and surface heap leaching uranium operation. Leach liquor was upgraded by ion exchange/solvent extraction and pregnant strip liquor was precipitated with ammonia for yellowcake production.

The wastes from this operation consisted of approximately 400,000 m^3 of precipitate sludge, made up of gypsum, iron hydroxides, thorium hydroxides and radium-barium sulphates, and 2 million tonnes of leached ore on surface. The leached ore was transferred to the waste sludge pond which was covered with sand and revegetated.

3.1.3 SASKATCHEWAN URANIUM PRODUCERS (1987)

3.1.3.1 General

The uranium producers in Saskatchewan are in the Athabasca Basin region in the north of the province. These include the Cluff Lake operation in the north-west, the Key Lake operation in the north-central part and the Rabbit Lake/Collins Bay operation on the eastern edge of the Athabasca Basin. Mill throughput capacity, ore grade, and estimated reserves of these three properties are summarized in Table 3.1.3-1.

The uranium deposits are within the Canadian Shield, a glacially scoured complex of geologically ancient rocks. The oldest rocks, more than 2 billion years old, are ancient Archean granites which comprise the basement complex. They are overlain and interfolded with a series of Aphebian age (1.7 to 2 billion years old) metamorphosed, deformed and recrystallized sediments which were derived from the basement rocks. The Athabasca Formation, of sandstone of Helikian age, was laid down on the older rocks approximately 1 billion years ago. The uranium mineralization is usually found near the contact between the Athabasca sandstone and the older rocks, or within highly altered Aphebian rocks. Uranium mineralization is commonly associated with significant structures and with arsenic, iron, nickel, cobalt, copper, zinc, molybdenum, lead, vanadium and sometimes thorium and selenium. A host of other minor minerals plus clay and graphite are commonly present, (SRK 1986).

TABLE 3.1.3-1
SASKATCHEWAN URANIUM PRODUCERS (1987)

Mine	Mill Capacity (tonnes/day)	Ore Grade (% U_3O_8)	Estimated Reserves at end 1986 (million kg U_3O_8)
Cluff Lake	800	0.5	17
Key Lake	720	2.4	73
Rabbit Lake/Collins/Eagle	2,000	0.61 to 2.5	100

3.1.3.2 Amok Cluff Lake

Cluff Mining operates mining and milling facilities in the Cluff Lake area of northern Saskatchewan. Amok Ltd., with its head office in Saskatoon, is the manager of the project.

Milling Operation

Phase I of the Cluff Lake operation, started in 1981 and completed in early 1983, was designed and built to recover uranium from the small, but very high-grade, "D" orebody. 54,000 tonnes of high-grade ore were processed to yield approximately 3,600 tonnes of uranium. The milling process for this phase consisted of gravity concentration, acid leaching, and direct precipitation of the leach liquor with magnesia. Wastes from this operation included leach residues, stored in concrete vaults on surface, and neutralized waste solutions containing a minimal amount of precipitates retained in a tailings pond, (SRK 1986).

The Phase I mill was modified in 1983 for re-processing gravimetric residue generated in the Phase I operation. This material, containing 2 to 3% U_3O_8, was re-processed in an acid leaching, filtration, solvent extraction circuit to produce a high-grade liquor for precipitation with magnesia. Neutralized tailings from this circuit were discharged to the Phase I tailings area. Re-processing of gravimetric residue was completed by early 1984 when a major modification and expansion of the Phase I mill was undertaken to allow the processing of uranium ores from other, lower grade orebodies in the Cluff Lake area.

This second phase of operation is referred to as the Cluff Mining Phase II operation. The Phase II ore, at approximately 0.5% U_3O_8, is considered a relatively clean ore by northern Saskatchewan standards since there are no arsenic or nickel minerals associated with the pitchblende mineralization, (Melis 1983). A typical analysis of the Phase II mill feed is given in Table 3.1.3-2, (Cluff Mining 1982).

The Phase II milling circuit, with a throughput of 230,000 tonnes per year, uses conventional crushing, grinding and sulphuric acid leaching of ore ground to minus 429 microns, at atmospheric pressure and low temperature (50°C), using sodium chlorate as oxidant. Liquid-solid separation is achieved by counter-current decantation (CCD) using five thickeners in series. Uranium recovery from pregnant solution is carried out in a solvent extraction circuit where uranium is extracted into an organic phase, which is subsequently stripped with sodium chloride solution to provide a high-grade strip solution for precipitation of uranium with magnesia. The organic phase consists of a tertiary amine (Alamine 336) and isodecanol in a kerosene carrier. Typical concentrations in the organic phase are 5%, 5% and 90% respectively. Spent organic is periodically regenerated with sodium carbonate solution and the sodium chloride solution is partially bled to the tailings neutralization circuit to prevent contaminant build-up in the solvent extraction circuit, (Clifton Associates 1986).

TABLE 3.1.3-2
TYPICAL ANALYSIS OF CLUFF *LAKE PHASE II* ORE

Element	%
U_3O_8	0.35-0.7
Th	0.0006
Ra-226	18 Bq/g
Si	33.1
Fe	1.5
S	0.03
Cu	0.008
Zn	0.007
Pb	0.015
Mo	0.02
V	0.02
Ni	0.003
Ti	0.015
Al	5.6
Bi	0.002
Ba	0.002
B	0.007
As	0.001
Ca	0.15
Mg	1.56
Na	0.06
K	1.3
P	0.04
CO_3	0.04
Cl	0.001
Total C	0.01

(from Cluff Mining 1982)

Waste Management

Tailings slurry from the mill (CCD tailings) is neutralized with lime, along with raffinate (barren solution) from the solvent extraction circuit and bleed streams of sodium chloride solution and sodium carbonate solution, as required. The neutralized tailings pulp is pumped to the waste management area where tailings decant water is treated with barium chloride, lime (if necessary) and coagulant. The treated effluent is partially clarified in settling ponds, with final clarification being achieved by sand filters prior to discharge. Sand filter backwash and settled precipitates are returned to the tailings area as required.

Surface storage of the Phase I leach residue in concrete vaults has not been considered a satisfactory method for long-term storage of this radioactive material. Amok is therefore reclaiming this material and processing it to recover the contained gold. The residue is then passed through the Phase II mill for additional uranium recovery. The leach residue would therefore be combined with the Phase II mill tailings and discharged to the Cluff Lake waste management area.

3.1.3.3 Key Lake

The Key Lake property is approximately 240 km north of La Ronge, Saskatchewan, 70 km east-southeast of Cree Lake. It is operated by Key Lake Mining Corporation of Saskatoon.

TABLE 3.1.3-3
TYPICAL ANALYSIS OF KEY LAKE ORE

Element	Gaertner Ore (%)	Deilmann Ore (%)
U_3O_8	2	2.9
Ra-226	222 Bq/g	N/A
SiO_2	50	50
Fe	3.5	3
S	1	0.8
Cu	0.03	0.09
Zn	0.08	0.03
Mo	0.006	0.03
V	0.08	0.09
Ni	1.9	1.1
Co	0.08	0.08
Ti	0.4	0.6
Al	9	10.3
As	1.2	1.1
Ca	0.4	0.4
Mg	3	2.9
Na	0.7	0.9
K	0.6	1.5
F	0.05	N/A
P_2O_5	0.16	0.15
CO_2	1	0.8
Cl	0.05	N/A

(from Melis Consulting Engineers 1986)

Ore Mineralogy

The Key Lake uranium deposit consists of two separate orebodies, the Gaertner and Deilmann orebodies. Both orebodies contain uranium mineralization (2 to 3% U_3O_8) associated with nickel arsenides and sulphides. Typical analyses of the two orebodies are listed in Table 3.1.3-3. The uranium ore minerals include euthedral and radially textured pitchblende (U_3O_8), and a smaller amount of coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$). Gersdorffite ((Ni,Co)AsS) is the most abundant nickel mineral followed by niccolite (NiAs) and bravoite ($(Ni,Fe)S_2$). Galena(PbS) of radiogenic origin is always present. Pyrrhotite ($Fe_{1-x}S$) and chalcopyrite ($CuFeS_2$) have been observed within the unaltered basement rocks. Extensive intergrowth of uranium and nickel minerals are present. Sooty pitchblende and coffinite can constitute the matrix for gersdorffite, millerite (NiS), niccolite and galena or vice versa.

Above the ore-bearing basement, uranium-nickel mineralization occurs intermittently in disseminated porous and fractured sandstone and conglomerate. Chlorite schist is the main uranium-nickel bearing host rock with quartzite host having a distinctly lower grade. In both the chlorite and quartzite hosts limonite ($FeO(OH.nH_2O)$), hematite (Fe_2O_3) and carbonates ($((Ca,Mg)CO_3)$) can accumulate in shear zones, cavities and fractures. Graphite (C) is present throughout the mineralization, see Clifton Associates (1986).

Milling Operation

The process and waste treatment circuit is shown in Figure 3.1.3-1.

At Key Lake the ore is ground in a semi-autogenous grinding (SAG) mill to a mesh-of-grind of minus 500 micron. The ground ore is dewatered in a thickener to a pulp density of 50% solids with the addition of a flocculant to assist in settling. The thickened pulp is then pumped to a two-stage leaching circuit where the ore is leached with sulphuric acid under oxidizing conditions. A two-stage circuit is used in order to recycle acid solutions for reducing overall acid consumptions and to prevent formation of ferric arsenate in the pregnant solution. This is done by providing reducing conditions, namely fresh ore feed, for the ferric iron contained in the recycled acid solution.

The ground ore is fed from storage pachucas (air agitated vessels) to first-stage pachucas where it is combined with reclaimed acid solution (thickener overflow solution) from the second-stage leach. The resulting pulp is leached at atmospheric pressure and relatively low pulp density and temperature. Oxidant requirements in the first-stage leach are met by the injection of air used for agitation in the pachucas. The ferric content in the thickener overflow solution also acts as an oxidant for the leaching reactions. Acid requirements for the first-stage leach are met by acid in the thickener overflow solution and by the addition of sulphuric acid as required.

The first-stage leach pulp is then pumped to the primary thickener where the thickener underflow is removed at 50% solids and pumped to the second-stage pressure leach feed tank. The overflow from the primary thickener is the pregnant solution which is pumped to solution pre-treatment ahead of the solvent extraction circuit.

Second-stage pressure leaching of the pre-leached ore slurry is carried out in a series of nine vertical pressure autoclaves. Sulphuric acid is added to the autoclave feed tank to provide the necessary acid levels for achieving high uranium extractions. Oxidant requirement is met by the injection of oxygen in the autoclaves. The second-stage leach slurry is then discharged into a surge tank for transfer to the eight-stage CCD circuit.

The overflow from the first-stage thickener in the CCD circuit is the acid solution recycled to the first-stage leaching step. Additional sulphuric acid is added in the CCD circuit in order to maintain adequate acid levels for preventing loss of uranium by reprecipitation. Minewater is used as wash water to wash uranium-containing solution from the leached ore. The underflow from the last CCD thickener is pumped to the tailings neutralization circuit.

Uranium in the pregnant solution from the CCD circuit is upgraded and purified in a solvent extraction circuit using a tertiary amine organic phase with ammonia stripping of loaded organic. The pregnant strip liquor is precipitated with ammonia to produce yellowcake and the barren strip solution from the precipitation circuit is recycled to the solvent extraction circuit. Ammonium sulphate concentrations in the strip liquor are controlled by removing a bleed stream of clarified strip solution to an ammonium sulphate crystallization circuit. The ammonium sulphate crystals are produced as fertilizer-grade material and marketed as 21-0-0 fertilizer. Spent organic is regenerated with sodium carbonate solution as required, (see Melis 1986).

Waste Management

The leach residue from the CCD circuit is neutralized with lime to pH 11 or greater and liquid waste streams are neutralized and treated in a separate waste treatment circuit.

In the liquid waste treatment circuit (referred to as the Bulk Neutralization circuit) raffinate and minor quantities of spent sodium carbonate solution from the solvent extraction circuit are first neutralized in a stepwise fashion with lime to pH 7. Seepage and supernatant water recycled from the tailings pond,

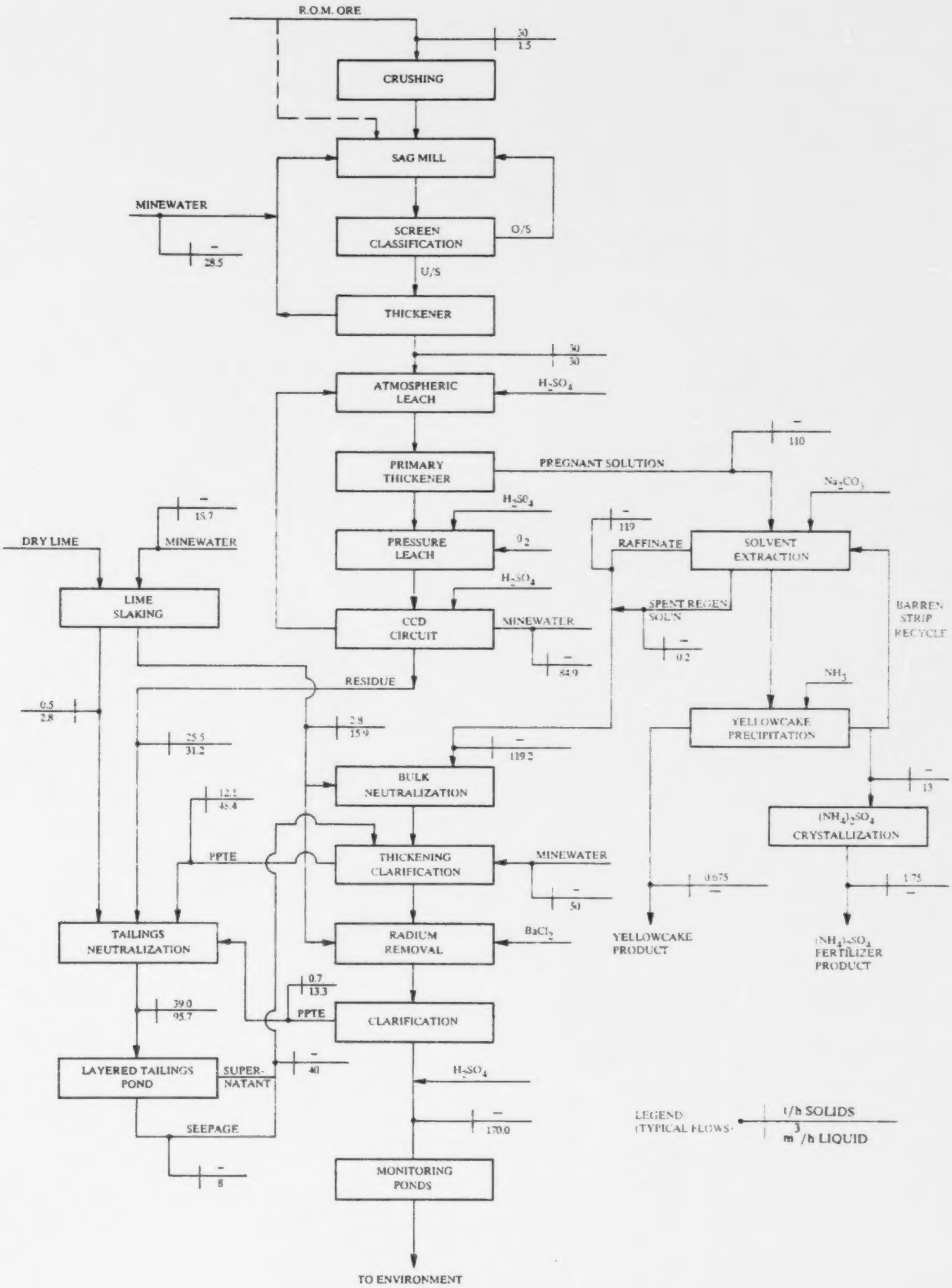

R.O.M. ORE
30
1.5
CRUSHING
SAG MILL
MINEWATER
–
28.5
SCREEN CLASSIFICATION
O/S
U/S
THICKENER
30
30
ATMOSPHERIC LEACH
H_2SO_4
–
110
PRIMARY THICKENER
PREGNANT SOLUTION
Na_2CO_3
H_2SO_4
–
15.7
DRY LIME
MINEWATER
–
119
RAFFINATE
SOLVENT EXTRACTION
PRESSURE LEACH
O_2
H_2SO_4
LIME SLAKING
SPENT REGEN SOL'N
BARREN STRIP RECYCLE
CCD CIRCUIT
MINEWATER
–
0.2
–
84.9
RESIDUE
NH_3
0.5
2.8
1
2.8
15.9
YELLOWCAKE PRECIPITATION
25.5
31.2
–
119.2
BULK NEUTRALIZATION
–
13
12.1
45.4
$(NH_4)_2SO_4$ CRYSTALLIZATION
PPTE
THICKENING CLARIFICATION
MINEWATER
0.675
–
1.75
–
–
50
TAILINGS NEUTRALIZATION
RADIUM REMOVAL
$BaCl_2$
YELLOWCAKE PRODUCT
$(NH_4)_2SO_4$ FERTILIZER PRODUCT
0.7
13.3
39.0
95.7
PPTE
CLARIFICATION
LAYERED TAILINGS POND
SUPER-NATANT
–
40
H_2SO_4
–
170.0
LEGEND (TYPICAL FLOWS)
t/h SOLIDS
m^3/h LIQUID
SEEPAGE
–
8
MONITORING PONDS
TO ENVIRONMENT

Figure 3.1.3-1 Key Lake Mill Process and Waste Treatment Circuits

along with excess minewater, are combined with the resulting precipitate slurry, and the diluted slurry is thickened to recover a bulk waste precipitate which is discharged to the mill tailings neutralization circuit. The thickener overflow is further treated with barium chloride and lime to pH 11 for removing radium and trace heavy metal contaminants. The minor amounts of additional precipitate produced in this second-stage treatment are removed in a thickener and pumped to the mill tailings neutralization circuit. The pH of the second-stage thickener overflow is adjusted with sulphuric acid and the resulting treated effluent is transferred to monitoring ponds. The effluent is either discharged to the environment, if contaminant levels are acceptable, or recycled for further treatment if necessary.

Minewater from the open-pit mining operation is used as process water and any excess contaminated water is treated in the waste treatment circuit. An ion exchange circuit has been used to treat excess tailings water. In this circuit radium is removed by a radium-selective ion exchange complexer and the treated water is discharged to the monitoring ponds.

The combined neutralized mill tailings, consisting of neutralized leach residue and waste precipitates, are pumped to the tailings containment area where a layered tailings deposition technique is used. The tailings slurry is deposited in thin layers in a rotational sequence and allowed to consolidate by evaporation and drainage. This systematic layered deposition method is claimed to provide a partially saturated, moisture retaining tailings mass of low permeability, with minimum potential for ongoing seepage. An underlying sand bed and perforated drainage pipe system removes vertical seepage during the deposition phase, and the main embankment incorporates a pervious upstream zone to decant precipitation and supernatant water continuously.

The seepage and supernatant water is pumped to lined water reservoirs at the mill site where the water is used as process water or treated for removal of radium, the only contaminant present above regulatory levels above regulatory levels, (Melis 1986).

3.1.3.4 Eldor Collins Bay/Rabbit Lake

The Rabbit Lake mining and milling facility, on the west side of Wollaston Lake, started operation under the management of Gulf Minerals Limited in June 1975. The operation was taken over by Eldorado Resources Limited (ERL) of Saskatoon in October 1982 and is currently being operated by Eldor Mines, a division of ERL.

Ore Mineralogy

The Rabbit Lake orebody, which was depleted in 1985, was relatively clean and similar in mineralogical characteristics to the Cluff Lake ore by virtue of its low nickel and arsenic content. The Collins Bay B-Zone ore on the other hand contains significant levels of arsenic and nickel. Typical analyses of both ores are presented in Table 3.1.3-4.

TABLE 3.1.3-4
TYPICAL ANALYSIS OF RABBIT LAKE AND COLLINS BAY B-ZONE ORES

Element	Rabbit Lake Ore (%)	Collins Bay B-Zone (%)
U_3O_8	0.3	0.6
ThO_2	N/A	0.003-0.04
Fe	N/A	1-3
S	N/A	0.1
Mo	0.002	0.01-0.02
V	0.02	0.02-0.05
Ni	0.01	0.4
As	0.003	0.5
Si	10.0	10.0
Zn	0.001-0.010	0.10-1.0
Bi	N/A	0.001-0.10
PO_4	0.2	0.02
CO_2	2-3	0.2
Ra-226(est.)	30 Bq/g	60 Bq/g

Note N/A = Not Available

The uranium mineralization in the B-Zone ore is made up of pitchblende (U_3O_8) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$). Associated mineralization includes gersdorffite ((Ni,Co)AsS), skutterudite ($((Co,Ni)As_2)$ niccolite (NiAs), millerite (NiS), galena (PbS), chalcopyrite ($CuFeS_2$) and pyrite (FeS_2). Elemental assemblages contain silver, arsenic, cobalt, chromium, copper, nickel, lead, titanium, vanadium and zirconium, (Clifton Associates Limited 1986).

Milling Operation

The process and waste treatment circuits for the Rabbit Lake and Collins Bay B-Zone ores are shown on Figures 3.1.3.2 and 3, respectively.

The Rabbit Lake mill, with a capacity of 2,200 tonnes per day, used a sulphuric acid atmospheric leach with sodium chlorate oxidant, CCD liquid-solid separation, solvent extraction with ammonium sulphate stripping and ammonia precipitation of uranium.

Run-of-mine ore was crushed in a jaw crusher prior to feeding a two- stage grinding circuit consisting of an open-circuit SAG mill and a closed-circuit ball mill. Cyclone overflow at 50 to 60% minus 74 microns was discharged directly to the leach circuit. Leaching was accomplished in a series of nine mechanically agitated tanks with a total retention time of nine hours. A leach temperature of 55°C and a sulphuric acid and sodium chlorate consumption of 90 kg/tonne and 3 kg/tonne respectively provided a uranium extraction efficiency of 96%.

Liquid-solid separation was accomplished in six CCD thickeners with a wash ratio of 2.5 to 1. The pregnant solution was clarified with a clarifying thickener and sand filters prior to solvent extraction. The solvent extraction circuit consisted of four extraction cells, four stripping cells and one solvent regeneration cell. The solvent was made up of tertiary amine (3.5%), isodecanol (3.5%) and kerosene (93%). Stripping of the loaded organic was accomplished with ammonium sulphate (130 g/l) at pH 3.8 to 4.1 controlled by gaseous ammonia sparging at a consumption rate of 0.6 kg NH_3/kg U_3O_8.

The uranium in the pregnant strip liquor was precipitated with ammonia (0.06 kg NH_3/kg U_3O_8) into a standard precipitation-washing circuit consisting of two precipitation tanks, two wash thickeners, a

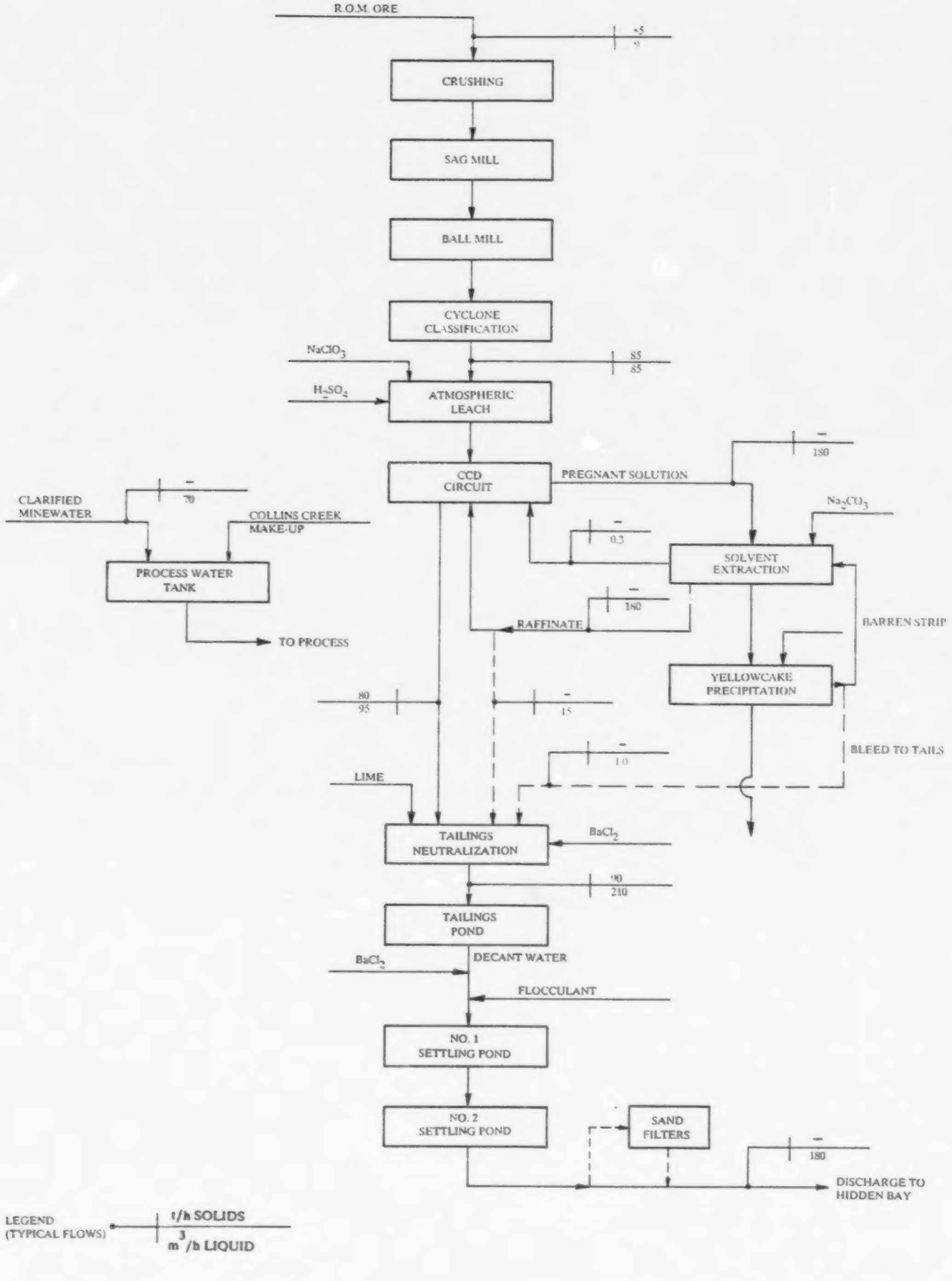

R.O.M. ORE
85
9
CRUSHING
SAG MILL
BALL MILL
CYCLONE CLASSIFICATION
NaClO3
85
85
H2SO4
ATMOSPHERIC LEACH
180
CCD CIRCUIT
PREGNANT SOLUTION
Na2CO3
CLARIFIED MINEWATER
70
COLLINS CREEK MAKE-UP
PROCESS WATER TANK
TO PROCESS
0.3
SOLVENT EXTRACTION
180
RAFFINATE
BARREN STRIP
YELLOWCAKE PRECIPITATION
80
95
15
BLEED TO TAILS
10
LIME
TAILINGS NEUTRALIZATION
BaCl2
90
210
TAILINGS POND
DECANT WATER
BaCl2
FLOCCULANT
NO. 1 SETTLING POND
NO. 2 SETTLING POND
SAND FILTERS
180
DISCHARGE TO HIDDEN BAY
LEGEND (TYPICAL FLOWS)
t/h SOLIDS
m3/h LIQUID

Figure 3.1.3-2 Rabbit Lake Ore Process and Waste Treatment Circuits

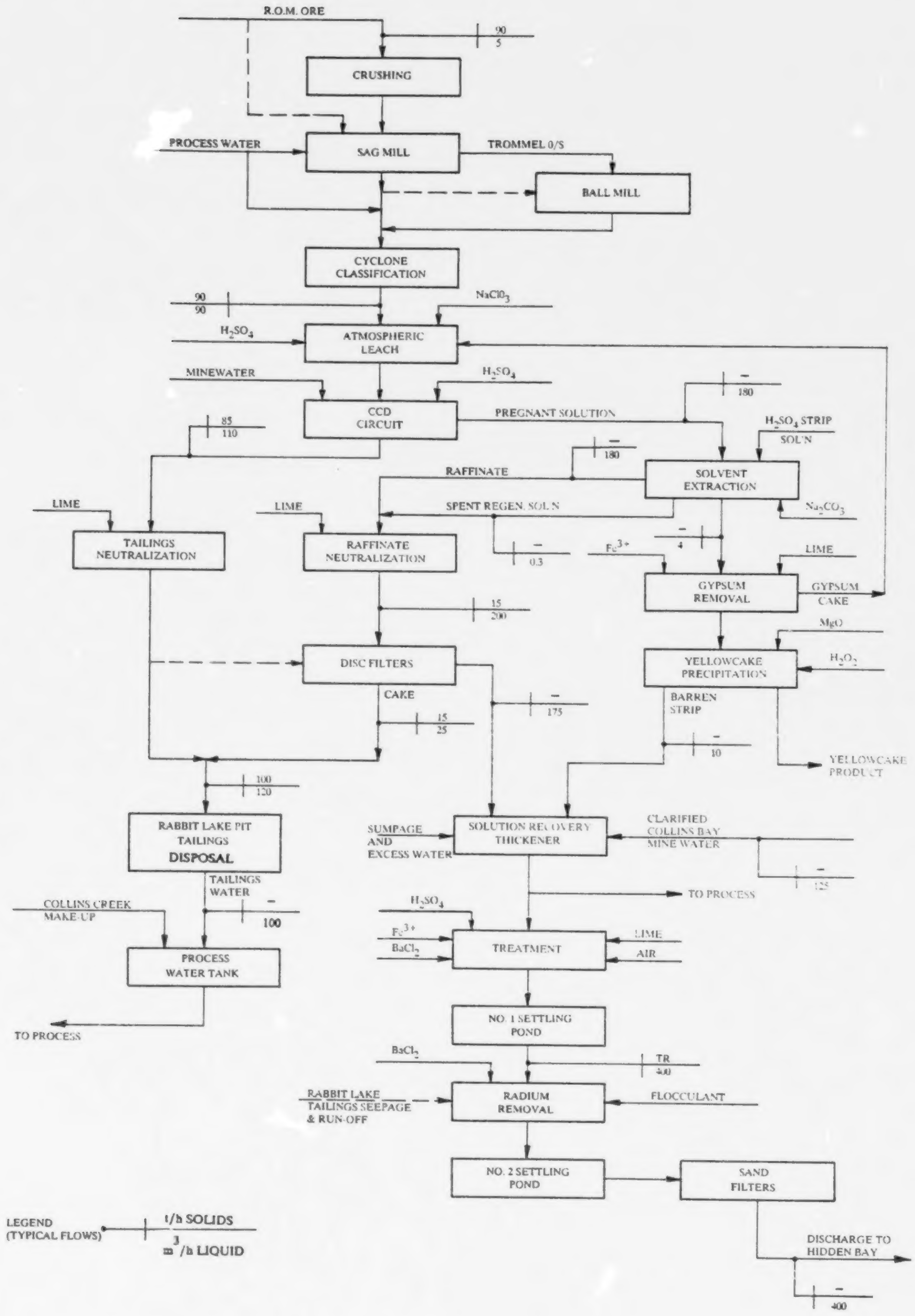

R.O.M. ORE
90
5
CRUSHING
PROCESS WATER
SAG MILL
TROMMEL O/S
BALL MILL
CYCLONE CLASSIFICATION
90
90
NaClO3
H2SO4
ATMOSPHERIC LEACH
MINEWATER
H2SO4
CCD CIRCUIT
PREGNANT SOLUTION
–
180
85
110
H2SO4 STRIP SOL'N
–
180
RAFFINATE
SOLVENT EXTRACTION
LIME
TAILINGS NEUTRALIZATION
LIME
SPENT REGEN. SOL'N
RAFFINATE NEUTRALIZATION
–
0.3
Na2CO3
–
4
Fe3+
LIME
GYPSUM REMOVAL
GYPSUM CAKE
15
200
MgO
DISC FILTERS
YELLOWCAKE PRECIPITATION
H2O2
CAKE
–
175
BARREN STRIP
15
25
–
10
YELLOWCAKE PRODUCT
100
120
RABBIT LAKE PIT TAILINGS DISPOSAL
SUMPAGE AND EXCESS WATER
SOLUTION RECOVERY THICKENER
CLARIFIED COLLINS BAY MINE WATER
–
125
TAILINGS WATER
–
100
COLLINS CREEK MAKE-UP
TO PROCESS
H2SO4
Fe3+
BaCl2
TREATMENT
LIME
AIR
PROCESS WATER TANK
TO PROCESS
NO. 1 SETTLING POND
BaCl2
TR
400
RABBIT LAKE TAILINGS SEEPAGE & RUN-OFF
RADIUM REMOVAL
FLOCCULANT
NO. 2 SETTLING POND
SAND FILTERS
LEGEND (TYPICAL FLOWS)
t/h SOLIDS
m3/h LIQUID
DISCHARGE TO HIDDEN BAY
–
400

Figure 3.1.3-3 Collins Bay B-Zone Ore Process and Waste Treatment Circuits (1987)

centrifuge and polishing filters for recycle strip solution. The yellowcake product was dried in a multi-hearth drier and packed into steel drums for shipment.

The Rabbit Lake milling circuit described above was modified to 1985 to process the nickel-arsenic bearing Collins Bay B-Zone ore. The main changes to the milling circuit included the use of strong acid (40% H_2SO_4) for stripping loaded organic in place of ammonium sulphate, pre-treatment of pregnant strip liquor to remove contaminants prior to uranium precipitation and the replacement of ammonia with hydrogen peroxide and magnesia for precipitating yellowcake, (Swider 1986).

Waste Management

From 1975 to 1985 neutralized tailings from the Rabbit Lake mill were deposited in the Rabbit Lake tailings pond which consists of a north and south earth-filled dam, constructed across an elongated valley between two north-south trending ridges, (Matich et al 1986). Tailings decant water from this area is treated with barium chloride and clarified in a series of three settling ponds as well as sand filters prior to discharge into Hidden Bay.

Waste treatment in the Collins Bay B-Zone circuit consists of neutralizing leach residues (CCD tails) and liquid effluents, mainly solvent extraction raffinate. The neutralized mill tailings are discharged to the mined-out Rabbit Lake pit. Neutralized mill tailings and waste precipitates were to be dewatered by filtration (disc filters) in order to accelerate the consolidation of tailings when placed in the Rabbit Lake pit. At present only the neutralized raffinate slurry is filtered. The collected precipitate is combined with the neutralized leach residue slurry for discharge into the Rabbit Lake pit. It is planned to incorporate at least partial filtration of the leach residue along with the raffinated slurry in order to increase the pulp density of the combined slurry discharging to the pit.

Clarified filtrate from the tailings filters, and excess minewater not used as process water, is treated in an effluent treatment circuit with ferric sulphate, lime and barium chloride for radium and trace arsenic removal. This treated effluent is discharged to the existing settling ponds at the Rabbit Lake tailings area where the water is treated further with barium chloride prior to clarification through sand filters for discharge to the environment.

3.1.4 ONTARIO URANIUM PRODUCERS (1987)

3.1.4.1 General

The Ontario uranium producers are all in the Elliot Lake area. The operating mines are the Quirke, Panel and Stanleigh mines operated by Rio Algom Limited and the Denison mine operated by Denison Mines Limited. Mill throughput capacity, and approximate ore grades for each mine, are summarized in Table 3.1.4-1. Compared with the northern Saskatchewan ores, those at Elliot Lake are relatively low-grade (0.1% U_3O_8).

TABLE 3.1.4-1
ONTARIO URANIUM PRODUCERS (1987)

Mine	Mill Capacity (tonnes/day)	Ore Grade (% U_3O_8)
Denison	11,000	0.09
Quirke	6,400	0.09
Panel	3,000	0.1
Stanleigh	4,500	0.075

3.1.4.2 Ore Mineralogy

The conglomerate ores presently being processed at the four uranium mines in the Elliot Lake area are all of the same mineralogical type. They are pyritic conglomerates, consisting essentially of quartz and chert pebbles in a matrix of sericitic, feldspathic quartzite containing pyrite (FeS_2), pyrrhotite ($Fe_{1-x}S$), titanium minerals, monazite ($((Ce,La,Y,Th)PO_4)$) and zircon ($ZrSiO_4$). There are a variety of radioactive minerals including brannerite ($(U,Ca,Fe,Th,(Ti,Fe)_2O_6)$), uraninite ($UO_2$), thucolite, uranothorite, uranothorianite, coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), allanite, xenotime (YPO_4), and gummite. Brannerite, uraninite, monazite, and uranothorite are the most important ore minerals.

A typical ore analysis for Elliot Lake conglomerate is given in Table 3.1.4-2. Although specific values would vary between each operation the values given are average values or expected ranges for the elements listed. It is also noted that the pyrite-pyrrhotite content of the ore is approximately 7% and the silica content is generally greater than 75%.

TABLE 3.1.4-2
TYPICAL ANALYSIS OF ELLIOT LAKE ORE

Element	%	Element	%
U_3O_8	0.1	Mn	0.004
Th	0.04	Cr	<0.001
Ra	11 Bq/g	Ba	0.02
L.O.I.	3	Cd	<0.001
SiO_2	80	Sb	<0.001
Fe	3-5	Sn	<0.001
S	2-4	B	0.004
Cu	0.007	As	<0.005
Zn	0.005	Ca	0.1
Pb	0.04	Mg	0.2
Mo	<0.001	Na	0.1
V	<0.001	K	2
Ni	0.003	F	0.02
Co	0.005	SO_4	<0.10
Ti	0.08	PO_4	0.1-0.2
Al	3-4	CO_2	0.2
Bi	<0.001	Cl-Br-I	0.005
Ag	<0.002	NH_3	0.02

(from Clifton Associates, 1986)

3.1.4.3 Denison

The Denison uranium mine, has been in continuous operation since 1957. The mill capacity has been increased to its present capacity of 11,000 tonnes per day, but it is currently operating at a rate of approximately 7,500 tonnes per day.

The milling circuit in use at the Denison operation is typical of Elliot Lake uranium operations. Ground ore from the SAG mill circuit (installed in 1979) is leached in pachucas with sulphuric acid at elevated temperature (80°C) and ambient pressure. Sodium chlorate is used as an oxidant for maximizing uranium extractions. The leach pulp discharges to wash thickeners for recovery of the uranium-bearing pregnant solution and preliminary washing of the leach residue. Wash thickener underflow is pumped to two-stage drum filters to wash the residue prior to neutralization and disposal to the tailings area.

The pregnant solution is clarified in leaf clarifiers prior to being pumped through the ion exchange circuit for recovery of the uranium. Barren solution is pumped to a new solvent extraction circuit (installed in 1986) for recovering yttrium contained in the ion exchange barren. The raffinate from this solvent extraction circuit is then recycled to the mill for use as wash in the liquid/solid separation circuit. Loaded resin is eluted with nitric acid to produce a concentrated eluate which is then precipitated with ammonia at pH 7 to produce ammonium diuranate (yellowcake). The yellowcake uranium product is dewatered, dried and packaged in drums for shipment.

Additional uranium is recovered from the Denison operation by bacterial leaching of mined-out or low-grade stopes underground. The acidic minewater, containing approximately 0.1 kg U_3O_8 per tonne of solution, is pumped to the grinding circuit and used as mill water. The uranium in the water is recovered in the leaching circuit during the transfer of slurry to the leach pachucas, (LaRocque, 1986).

Tailings slurry from the mill (re-pulped drum filter discharge) is bulk neutralized with limestone then with lime to pH 10 to 11, prior to being pumped to the Long Lake tailings basin or to the underground backfill cyclone plant. Approximately 50 million tonnes of tailings have been deposited in the tailings containment areas since the start of operations. Tailings decant water is treated with barium chloride for removal of radium and then discharged to Stollery Lake which is separated by a dyke to allow settling of the precipitated sludge before discharge into the Serpent River system.

3.1.4.4 Rio Algom Quirke

The Quirke mine and mill is approximately 15 km north of Elliot Lake. The facility was operated first from 1956 to 1961, and was re-started in 1968 when the Nordic Mine ceased operation.

The Quirke milling circuit with a capacity of 6,400 tonnes per day, includes acid leaching, ion exchange and ammonia precipitation for uranium recovery. The process and waste treatment circuit is shown in Figure 3.1.3.4. Ore is ground in a conventional rod mill-pebble mill grinding circuit and the pulp is dewatered in thickeners and disc filters ahead of leaching. The ore is leached with sulphuric acid at high pulp density (2,000 g/l) in air-agitated pachucas at 80°C. Sodium chlorate is not used since the agitation air meets the oxidation requirements of the pulp.

Pregnant solution is recovered in a liquid/solid separation wash circuit consisting of five stages of wash cyclones for the coarse slurry and six stages of CCD thickeners for the slimes. The pregnant solution is clarified in leaf clarifiers and upgraded in an ion exchange circuit by nitric acid elution of loaded resin. The concentrated eluate is precipitated with ammonia and the yellowcake slurry is trucked to a common drying and packing plant at the Nordic minesite. Uranium recovery from minewater is achieved by precipitation of acidic minewater with lime and re-dissolution of the uranium-containing precipitate.

Tailings slurry, consisting of CCD tailing slimes and coarse washed cyclone underflow, is neutralized with limestone to pH 3.5 and lime to pH 10 to 11 in a series of five tailings neutralization pachucas. The neutralized tailings slurry is pumped to the Bud Lake tailings basin where tailings decant water and acidic seepage water is treated with lime and barium chloride. The treated water is clarified in a series of three unlined settling ponds prior to discharge to the Serpent River system. Approximately 32 million tonnes of tailings have been discharged into the tailings basin to date.

3.1.4.5 Rio Algom Panel

Rio Algom operated the Panel mine and mill facility on the shore of Quirke Lake between 1958 to 1961, and re-commenced operations in 1979.

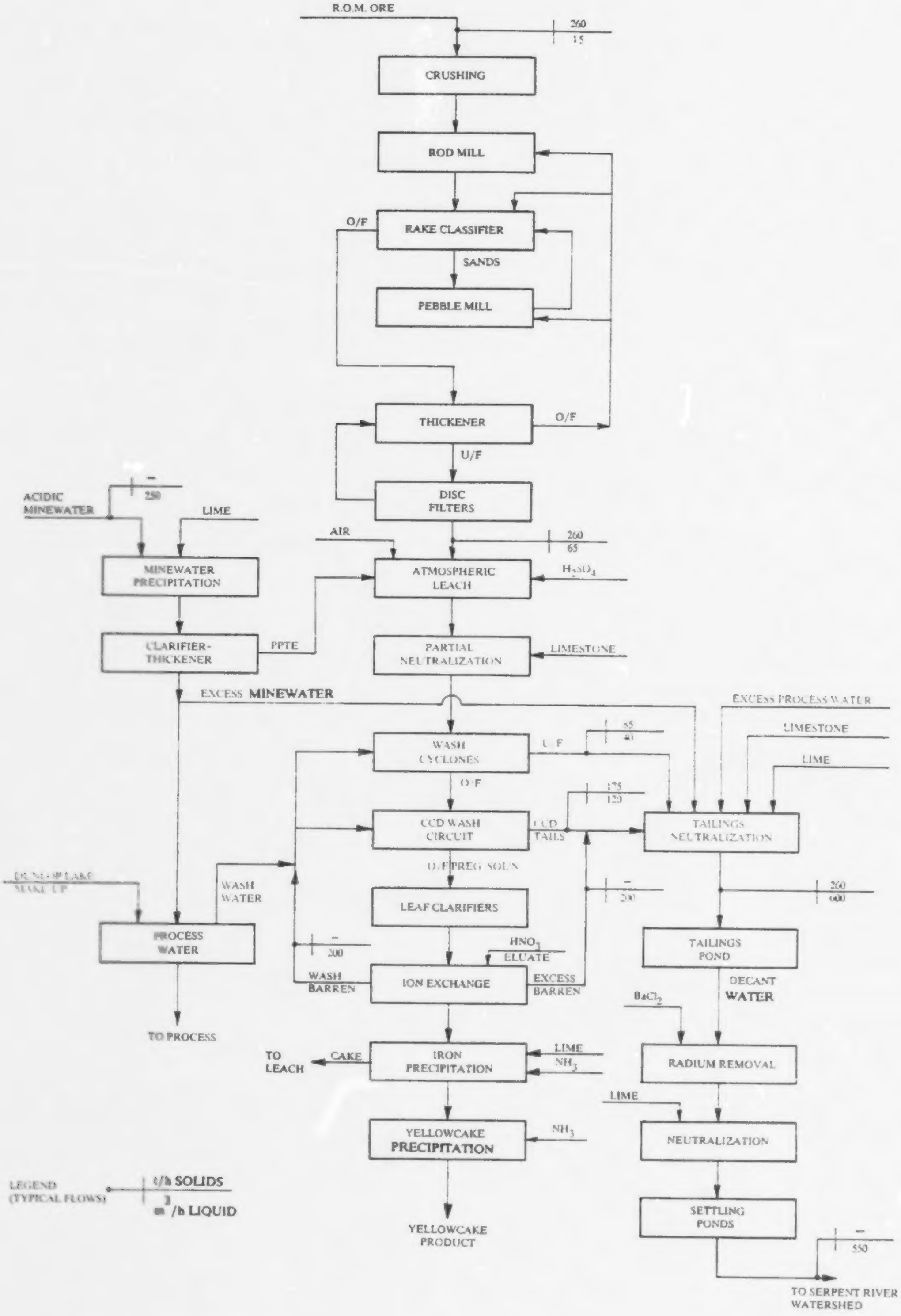

R.O.M. ORE
260
15
CRUSHING
ROD MILL
O/F
RAKE CLASSIFIER
SANDS
PEBBLE MILL
THICKENER
O/F
U/F
DISC FILTERS
ACIDIC MINEWATER
—
250
LIME
AIR
260
65
MINEWATER PRECIPITATION
ATMOSPHERIC LEACH
H2SO4
CLARIFIER-THICKENER
PPTE
PARTIAL NEUTRALIZATION
LIMESTONE
EXCESS MINEWATER
EXCESS PROCESS WATER
LIMESTONE
LIME
WASH CYCLONES
U/F
55
40
O/F
175
120
CCD WASH CIRCUIT
CCD TAILS
TAILINGS NEUTRALIZATION
O/F PREG SOL'N
DUNLOP LAKE MAKE-UP
WASH WATER
LEAF CLARIFIERS
—
200
260
600
PROCESS WATER
—
200
HNO3
ELUATE
TAILINGS POND
WASH BARREN
ION EXCHANGE
EXCESS BARREN
DECANT WATER
TO PROCESS
BaCl2
TO LEACH
CAKE
IRON PRECIPITATION
LIME
NH3
RADIUM REMOVAL
LIME
YELLOWCAKE PRECIPITATION
NH3
NEUTRALIZATION
LEGEND (TYPICAL FLOWS)
t/h SOLIDS
m3/h LIQUID
SETTLING PONDS
YELLOWCAKE PRODUCT
—
550
TO SERPENT RIVER WATERSHED

Figure 3.1.3-4 Quirke Mill Process and Waste Treatment Circuits

The milling process at Panel, with a capacity of 3,000 tonnes per day, is similar to the Denison operation except that grinding is by conventional rod-pebble mills, loaded resin is eluted with 10% sulphuric acid, and yellowcake precipitation is by magnesium oxide. A circuit change to sulphuric acid elution and magnesia precipitation was made to eliminate the problem of elevated ammonia levels in tailings decant water. Similarly to the Quirke operation, yellowcake slurry is trucked to the Nordic drying and packing plant where it is packed in drums for shipment. As with the other Elliot Lake operations, uranium is recovered from minewater by precipitation with lime.

Tailings slurry from the mill is bulk neutralized with limestone and lime, then pumped to the Strike Lake tailings area. A total of approximately 10 million tonnes of tailings have been deposited to date. Tailings decant water is collected and treated with lime and barium chloride for radium removal and neutralization. The treated effluent is clarified in hypalon-lined settling ponds prior to discharge into Quirke Lake, see photo 3.1.3

Photo 3.1-3 Quirke Mine tailings disposal, Elliot Lake, Ontario.

3.1.4.6 Rio Algom Stanleigh

The Stanleigh mine, currently owned by Rio Algom and Ontario Hydro, first operated from 1958 to 1960. It was put back into production in 1983 under the management of Rio Algom.

The Stanleigh milling circuit, with a rated capacity of 4,500 tonnes per day, includes SAG milling, acid leaching in air-agitated pachucas, recovery of uranium-bearing pregnant solution by horizontal belt wash filters, continuous moving bed ion exchange (Himsley) system, sulphuric acid elution of loaded resin and magnesia precipitation of uranium. The process and waste treatment circuit is shown in Figure 3.1.3.5.

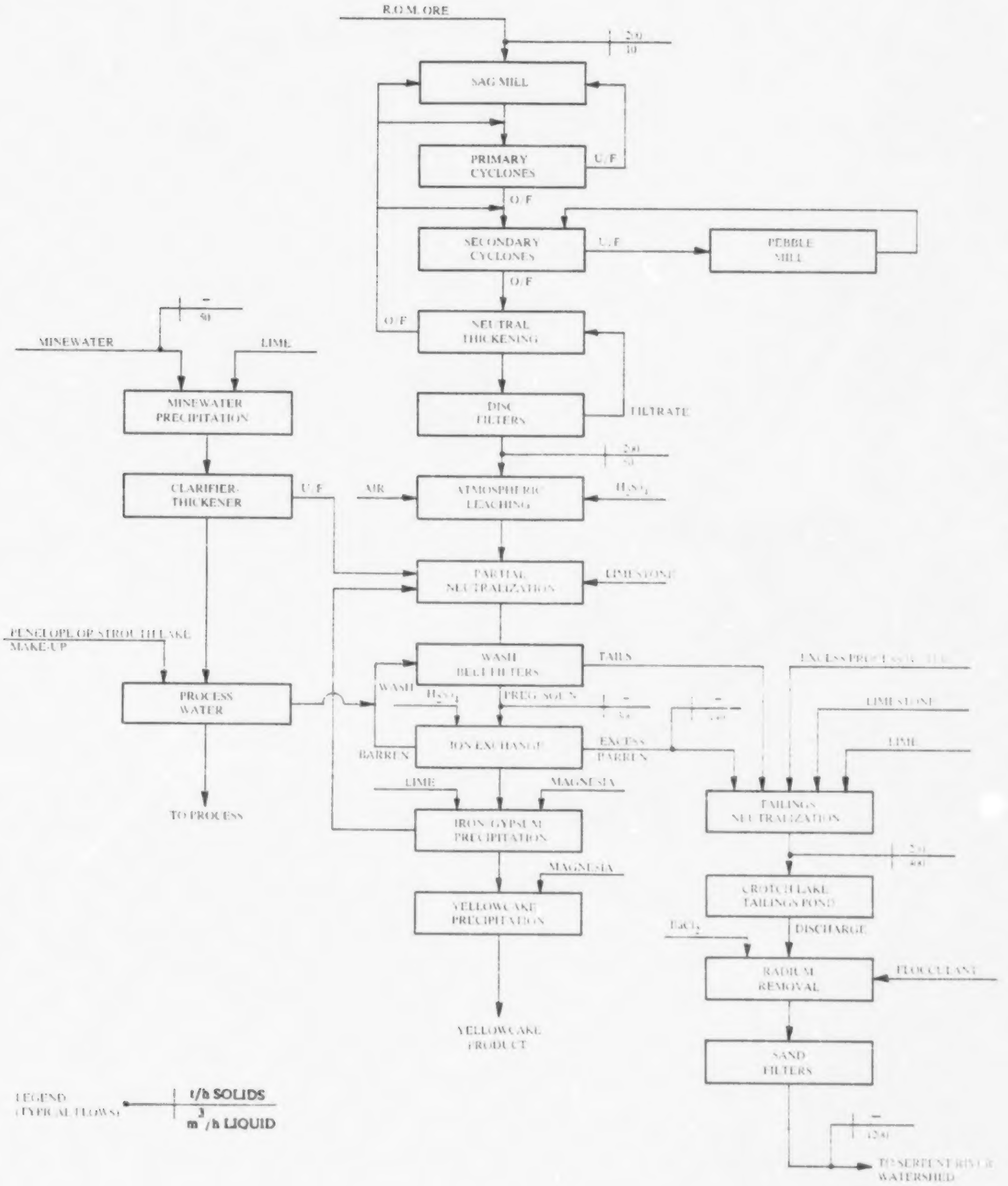

R.O.M. ORE
200
10
SAG MILL
PRIMARY CYCLONES
U/F
O/F
SECONDARY CYCLONES
U/F
PEBBLE MILL
O/F
O/F
NEUTRAL THICKENING
DISC FILTERS
FILTRATE
200
50
MINEWATER
—
50
LIME
MINEWATER PRECIPITATION
CLARIFIER-THICKENER
U/F
AIR
ATMOSPHERIC LEACHING
H_2SO_4
PARTIAL NEUTRALIZATION
LIMESTONE
PENELOPE OR STROUTH LAKE MAKE-UP
PROCESS WATER
TO PROCESS
WASH BELT FILTERS
TAILS
WASH
H_2SO_4
PREG. SOL'N
—
BARREN
ION EXCHANGE
EXCESS BARREN
—
EXCESS PROCESS WATER
LIMESTONE
LIME
LIME
MAGNESIA
IRON/GYPSUM PRECIPITATION
TAILINGS NEUTRALIZATION
200
400
MAGNESIA
YELLOWCAKE PRECIPITATION
CROTCH LAKE TAILINGS POND
DISCHARGE
$BaCl_2$
RADIUM REMOVAL
FLOCCULANT
YELLOWCAKE PRODUCT
SAND FILTERS
LEGEND (TYPICAL FLOWS)
t/h SOLIDS
m^3/h LIQUID
—
1200
TO SERPENT RIVER WATERSHED

Figure 3.1.3-5 Stanleigh Mill Process and Waste Treatment Circuits

Tailings slurry is bulk neutralized with limestone and lime and pumped to the Crotch Lake tailings area where the neutralized tailings are deposited over old tailings from the previous Stanleigh and Milliken mine operations. Approximately 11 million tonnes of tailings are in the containment area. Tailings decant water is treated with lime and barium chloride for neutralization and radium removal at a separate treatment plant located at the discharge of Crotch Lake. Clarification of treated effluent is accomplished by sand filtration with dual-media sand filters. The precipitated sludge, as sand filter backwash, is returned to the tailings area.

3.1.5 FUTURE AND POTENTIAL URANIUM PRODUCERS

3.1.5.1 General

The future of uranium production in Canada probably lies with the high-grade uranium deposits in northern Saskatchewan. These include the Cigar Lake deposit as well as the smaller Midwest, Dawn Lake, and McClean Lake sources. There are additional deposits associated with the Rabbit Lake-Collins Bay operation of Eldor Mines. These include the significant Eagle Point deposit and the Collins Bay A-Zone, and D-Zone deposits immediately north of Rabbit Lake, as well the smaller Raven, Horseshoe and West Bear deposits south of Rabbit Lake. Another area of promise is the Baker Lake area in the Northwest Territories where the Kiggibik (Lone Gull) deposit has been discovered. Estimated ore grades and uranium reserves for these currently known deposits are summarized in Table 3.1.5-1.

TABLE 3.1.5-1
FUTURE AND POTENTIAL CANADIAN URANIUM PRODUCERS

Deposit	Grade (%U_3O_8)	Estimated Reserves (million kg U_3O_8)
Cigar Lake-Main Pod	14	130
Cigar Lake-Western Extention	5	45
Midwest	2-2.5	14
Dawn Lake	2	13.6
McClean Lake	1.8	6.4
Eagle Point North	2	24
Eagle Point South	2	40
Collins Bay A-Zone	5.7	7.7
Collins Bay D-Zone	2.2	2.5
Kiggibik	0.4	17

(from Melis et al 1983, SMDC 1985, Saracoglu et al 1983, Homenuke 1986, Fuchs et al 1982)

Uranium discoveries have been made in the Kelowna area of British Columbia (Blizzard), in Nova Scotia and in Newfoundland (Kitts/Michelin). These deposits are small and of lower grade in comparison to the deposits in northern Saskatchewan. Uranium production from these areas in the near future is unlikely since public pressure has led to moratoriums in B.C. and Nova Scotia and to rejection of the Environmental Impact Assessment for the property in Newfoundland. The lifting of the moratorium on uranium exploration in B.C. may lead to future development in that province.

3.1.5.2 Cigar Lake

The large high-grade Cigar Lake orebody, discovered by the French owned company, Cogema Canada Ltd., is immediately south of Waterbury Lake, approximately 115 km northeast of the Key Lake mine or 55 km west-southwest of Eldor Mines' operations at Rabbit Lake. This project is managed by Cigar Lake Mining Corporation of Saskatoon. Pre-development studies for the Cigar Lake Project are currently underway in preparation for an underground test mine entry in 1988-1989. Production from this deposit is slated for the early 1990's.

A typical analysis of the Cigar Lake ore is given in Table 3.1.5-2. The uranium in this high-grade deposit occurs as uraninite (UO_2) and pitchblende (U_3O_8) with coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) being present in smaller quantities. The sulfo-arsenides of nickel and cobalt can locally be major components of the ore with the main minerals being gersdorffite ($(Ni,Co)AsS$), skutterudite ($(Co,Ni)As_2$), niccolite ($NiAs$), bravoite ($(Ni,Fe)S_2$), cobaltite ($(Co,Fe)AsS$), and rammelsbergite ($(Ni,Co,Fe)As_2$). The sulfide minerals pyrite (FeS_2), marcasite (FeS_2), pyrrhotite ($Fe_{1-x}S$), smythite ($AgAsS_2$), chalcopyrite ($CuFeS_2$), covellite (CuS), bornite (Cu_5FeS_4), galena (PbS), jordisite (MoS_2), and sphalerite (ZnS) are present in varying but generally smaller amounts.

TABLE 3.1.5-2
TYPICAL ANALYSIS OF CIGAR LAKE DEPOSIT

Element	%
U_3O_8	14
Cu	0.7
Zn	0.04
Pb	1.2
Mo	0.14
Ni	1
Co	0.15
As	1.7
Ra(est)	1450 Bq/g

(from Clifton Associates 1986)

3.1.5.3 Midwest Deposit

The Midwest uranium deposit is northwest of the Rabbit Lake/Collins Bay minesite. A typical analysis of the ore is given on Table 3.1.5-3.

TABLE 3.1.5-3
TYPICAL ANALYSIS OF MIDWEST DEPOSIT

Element	%
U_3O_8	2.2
Ra-226	275 Bq/g
L.O.I.	3.1
SiO_2	76
Fe	1.3
S	1.1
Cu	0.1
Zn	0.07
Mo	0.06
V	0.08
Ni	1.7
Co	0.2
Ti	0.3
Al	3.2
Mn	0.04
Cr	0.02
As	3.2
Ca	0.1
Mg	0.5
Na	0.1
K	1.2
F	0.05
P	0.03
CO_2	0.5
Cl	0.03
Zr	0.05
Rb	0.05
Sr	0.01

(from Melis et al 1983)

Although there are no immediate plans to develop this property, extensive metallurgical work has been done on the ore which established that a Key Lake-type milling circuit would be suitable for the nickel, arsenic-bearing uranium ore, (Melis et al 1983).

The principal minerals in the Midwest deposit include pitchblende (U_3O_8), coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), gersdorffite ((Ni,Co)AsS), niccolite (NiAs), rammelsbergite ($((Ni,Co,Fe)As_2)$). Also present are minor amounts of chalcopyrite ($CuFeS_2$), galena (PbS), bismuthinite (Bi_2S_3) polydimite (Ni_3S_4), and cobalt and silicate minerals. The pitchblende nickel-arsenide veins are associated with kaolinite-chlorite ($Al_4Si_4O_{10}(OH)_8$ $(Mg,Al,Fe)_{12}(Si,Al)_8)O_{20}(OH)_{16}$) and sericite ($K_2Al_4Si_6Al_{20}O_{20}(OH,F)_4$).

3.1.5.4 Dawn Lake

The Dawn Lake deposit is northwest of the Rabbit Lake/Collins Bay minesite. It is made up of several "pods".

The mineralogy of the ore is pitchblende (U_3O_8), uraninite (UO_2) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) as uranium minerals with nickel arsenides, carbonates and goethite (FeO(OH)) being present as other constituents. Most minerals include quartz (SiO_2), chlorite ($((Mg,Al,Fe)_{12} (Si,Al)_8O_{20}(OH)16)$, illite ($(K_{1-1.5}Al_4Si_{7-6.5}Al_{1-1.5}O_{20}(OH)_4)$), sericite ($(K_2Al_4Si_6Al_2O_{20}(OH,F)_4)$) and titanium oxides ($(TiO_2)$).

3.1.5.5 McClean Lake

The McClean deposit, midway between the Dawn Lake deposit and the Rabbit Lake/Collins Bay minesite, is made up of two deposits, McClean North and McClean South. A third deposit associated with this property is the JEB deposit which was discovered in 1982, but uranium reserves have not yet been established.

The McClean uranium mineralization is concentrated in four facies. The sulphide facies consists of bravoite-pyrite ($((Ni,Fe)S_2\text{-}FeS_2)$), coffinite ($(U(SiO_4)_{1-x}(OH)_{4x})$), uraninite ($(UO_2)$), iron chlorite ($(Fe_{12}(SiAl)_8O_{20}(OH)_{16})$), illite ($(K_{1-1.5}Al_4Si_{7-6.5}Al_{1-1.5}0_{20}(OH)_4)$), siderite ($(FeCO_3)$) and chalcopyrite ($(CuFeS_2)$). The arsenide facies occur as arsenide-illite intergrowths, pararammelsbergite ($(NiAs_2)$), niccolite (NiAs), gersdorffite ((Ni,Co)AsS) and safflorite ($((Co,Fe,Ni)As_2)$). A bleached facies contains nodular intergrowths of coffinite-pararam/melsbergite and illite with subordinate nicollite, gersdorffite and arsenides. The oxide facies contains nodular intergrowths of coffinite-pararammelsbergite in hematized clay.

3.1.5.6 Eagle Point/Collins Bay A-Zone, D-Zone

The Eagle Point deposit, which forms part of the uranium reserves for the Eldor Mines Rabbit Lake/Collins Bay operation, contains two deposits, Eagle Point North and Eagle Point South.

The Eagle Point deposit contains pitchblende ((U_3O_8)), coffinite ($(U\text{-}(SiO_4)_{1-x}(OH)_{4x})$), uranophane ($(Ca(UO_2)_2)SiO_3)(OH)_{2.5}H_2O)$) and boltwoodite ($(K_2(U_O2)(SiO_3)_2(OH)_{2.5}H_2O)$). Associated minerals include gersdorffite ((Ni,Co)AsS), millerite (NiS), chalcocite ((Cu_2S)) and galena (PbS).

The Collins Bay A-Zone orebody contains pitchblende ((U_3O_8)) associated with rammelsbergite ($((Ni,Co,Fe)As_2)$), pararammelsbergite ($(NiAs_2)$) and some galena (PbS) and sphalerite (ZnS).

3.1.5.7 Kiggibik (Lone Gull)

The Kiggibik deposit is in the Baker Lake area of the Keewatin District in the Northwest Territories. The deposit, approximately 80 km west of the community of Baker Lake, was discovered in 1977 by Urangesellschaft Canada.

A typical analysis of the Kiggibik ore is given in Table 3.1.5-4. The most common uranium minerals in the deposit are pitchblende ((U_3O_8)) and coffinite ($(U(SiO_4)_{1-x}(OH)_{4x})$) with minor amounts of uranophane ($(Ca(UO_2)_2)Si_2O_7).5H_2O)$) being identified. Uranium vanadates have been identified and uraniferrous titanates are possibly present in minor amounts. The pitchblende and coffinite contain fine-grained inclusions of marcasite ((FeS_2)), pyrite ((FeS_2)), chalcopyrite ($(CuFeS_2)$), rutile ((TiO_2)), and, less commonly, galena (PbS). The most common sulphide mineral is marcasite with marcasite-pyrite-pitchblende-coffinite intergrowths being fairly common. The common gangue minerals are quartz ((SiO_2)), sericite ($(K_2Al_4Si_6Al_2O_{20}(OH,F)_4)$), illite ($(K_{1-1.5}Al_4Si_{7-6.5}Al_{1-1.5}\ O_{20}(OH)_4)$), and chlorite ($((Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16})$). Minor smectite group clays are locally present, and minor to trace amounts of barite ($(BaSO_4)$), apatite ($(Ca_{10}F_2(PO_4)_6)$) and rare earth phosphates have been detected.

TABLE 3.1.5-4
TYPICAL ANALYSIS OF KIGGIBIK DEPOSIT

Element	%
U_3O_8	0.4-0.75
ThO_2	0.002
SiO_2	60
Fe	2.7
S	0.1
Cu	0.002
Pb	0.02
Mo	0.02
V	0.07
Ni	0.002
Co	0.003
Ti	0.3
Al	9.9
Mn	0.04
Sb	0.007
B	0.05
As	0.03
Ca	0.3
Mg	1.2
Na	0.09
K	4.1
Zr	0.02
Hg	0.00005
Ag	4.2 g/t
Au	0.4 g/t
Ra-226(est)	75 Bq/g

(from Clifton Associates 1986)

3.2 CHEMICAL/MINERALOGICAL CHARACTERISTICS - EFFECTS ON DISPOSAL TECHNOLOGY

3.2.1 OVERVIEW

The main chemical factors which effect or influence the technology of disposal of a specific uranium tailings material are:

- grade, which impacts the economics of processing and disposal and radiological considerations,
- acid generation potential and its effect on long-term aqueous discharges,
- contaminants such as arsenic which can be an environmental concern in both air and water releases,
- chemical precipitates as they relate to long-term stability, physical properties and the chemistry of a tailings pile, and
- radiological considerations such as radon, gamma radiation, and water soluble radionuclides.

Each of these characteristics are reviewed in the following sections.

3.2.2 URANIUM GRADE

Uranium tailings deposits in Canada span a wide range in uranium content. Current operations are mining ores with U_3O_8 content as low as 0.08 percent in the Elliot Lake area to more than 40 percent in northern Saskatchewan. Typical mill feed grades in each area are 0.1 and 2 percent U_3O_8 respectively. Therefore a low-grade operation produces 20 times more tailings per unit of uranium product than for the high-grade ores. With the high grade tailing, the radionuclides are concentrated into a small volume leading to higher specific activity and greater radiological concerns.

NUTP undertook an evaluation of milling alternatives, see SENES (1986a), which assessed the relative costs of tailings disposal for low-grade (0.1 percent), medium-grade (0.4 percent) and high-grade (2.0 percent) uranium deposits. The relative costs for each generic facility are summarized on Table 3.2-1. Disposal costs include operating costs, reclamation costs and long-term management costs where appropriate. The study demonstrated that for the generally accepted disposal and close-out technology, disposal cost per kg of uranium recovered were similar. However, the disposal cost per tonne of tailings increases dramatically with grade. Given the current market value of uranium in the \$50 to \$70/kg range, it is highly unlikely that the processing facilities for low, even medium-grade ore could economically adopt the highly engineered disposal facilities proposed for the high-grade ores.

TABLE 3.2-1
TAILINGS DISPOSAL COSTS[1]

		Grade	
	Low[2] 0.1% U_3O_8	Medium[2] 0.4% U_3O_8	High[3] 2.0% U_3O_8
Production (kg/yr-U_3O_8)	2.3×10^6	2.3×10^6	2.3×10^6
Tailings Production (t/yr)	2.66×10^6	$.595 \times 10^6$	$.115 \times 10^6$
Disposal Cost (\$/kg-U_3O_8)	2.22	0.9	1.77
Disposal Cost (\$/t tailings)	1.88	3.41	34.70

[1] (Based on SENES 1986a)

[2] Cost is based upon valley dam, shallow cover with vegetation for reclamation and perpetual treatment

[3] Cost is based upon above ground engineered impoundment with a multi-engineered barrier cover for reclamation

Increasing regulatory requirements for uranium mines have led to changes in Canadian uranium processing methodologies in order to meet the more stringent guidelines established for effluent quality. Not only have certain components of uranium milling circuits changed but various waste treatment circuits have been incorporated into uranium processing design depending on the contaminant characteristics of the ore being processed. These changes have been introduced both in the Elliot Lake area uranium mines and, more recently, in northern Saskatchewan uranium operations.

Descriptions of the process and waste treatment circuits of uranium mines in these two areas were given in Sections 3.1.3 and 3.1.4, and by comparison it can be seen how recent technology has adapted to meet the increased regulatory requirements.

Of the four uranium mines in the Elliot Lake area, the Quirke and Stanleigh operations offer a good comparison of different technologies being used for processing similar uranium ore. The evolution of technological change for the processing of uranium ore at northern Saskatchewan mines was necessary for several reasons. The changing metallurgical characteristics of the high-grade uranium ores necessitated process changes which could accommodate the high arsenic and heavy metal content of the ore. Increasing regulatory requirements led to the introduction of relatively sophisticated waste management schemes. The arsenic and heavy metal content of some of the high-grade ores resulted in more elaborate waste treatment circuits being necessary to effectively remove all contaminants from mill effluents. A comparison of recently established northern Saskatchewan uranium mills to the first-generation Rabbit Lake mill in the Athabasca Basin region provides insight into the technological changes that have evolved.

3.2.3 ACID GENERATION

Sulphide minerals are common in most uranium deposits in Canada. Sulphides such as pyrrhotite and some forms of pyrite are very reactive and tend to be subjected to both chemical and biological oxidation in surface tailings deposits. The potential for acid generation depends upon ore type, process and method tailings disposal. The mechanisms associated with sulphide oxidation have been reviewed extensively by NUTP (SENES 1984, SENES 1986b, Hester 1984, Beak 1986).

In summary, in the presence of moisture and oxygen, sulphides are oxidized to sulphuric acid which can produce low pH conditions and excessive acidity in seepage and runoff from uranium tailings.

In Canada, acid generation at uranium tailings areas is a major concern. Because tailings have almost universally been leached with a strong sulphuric acid solution, the tailings have very little natural buffering capacity. Carbonate minerals are invariably absent, or present only at low concentrations. The presence of carbonate minerals is normally attributed to limestone in lime used for neutralization, or to unreacted limestone used in partial neutralization.

The production of acid conditions can result:

- elevated levels of heavy metals and selected radionuclides in runoff and seepage,
- downstream pH depression, and
- large quantities of acid mine drainage sludge if treatment is practiced.

The primary factors affecting the oxidation rate are sulphide content, temperature, and oxygen availability.

Of the active or recently decommissioned facilities, only Elliot Lake has a major acid generation problem. A typical analysis of contaminated porewater from an Elliot Lake tailings deposit is presented in Table 3.2-2. For those deposits with 5 to 10 percent pyrite, acid conditions are expected to last for more than one hundred years and the resultant sludge may in itself require an engineered disposal facility. The high-grade uranium deposits have elevated sulphide contents but are not expected to produce highly acidic runoff. Carbonate levels are typically elevated and with the very high moisture contents in combination with the low ambient temperatures and potential freezing conditions, acid production rates should be low.

TABLE 3.2-2
POREWATER CONTAMINANT LEVELS IN THE OXIDIZING AND NON-OXIDIZING ZONES OF ELLIOT LAKE TAILINGS

Parameter	Measurement Units	Typical Range Oxidizing Zone	Typical Range Non-Oxidizing Zone
pH	-	1-3	5-7
Acidity	mg/L	2000-10000	2000-12000
Cu	mg/L	0.1-0.3	<0.1
Pb	mg/L	0.5-2	<0.1-1
Ni	mg/L	2-20	0.3-1
Zn	mg/L	1-10	0.5-2
Fe^{2+}	mg/L	0-2000	500-3000
Fe^{3+}	mg/L	0-1000	<10
Mn	mg/L	2-40	2-40
SO_4	mg/L	2000-10000	2000-12000
Pb-210	Bq/L	little data	<0.02
Th-230	Bq/L	1000-10000	<2
Ra-226	Bq/L	2-8	2-8
U	mg/L	1-10	<1

(from SENES 1984)

The Bancroft low grade tailings have low acid generation potential although pyrite oxidation and minor pH depressions have been recorded. The pH levels do, however, stay in the 4.5 to 7.0 range. Similar results are expected for Cluff Mining Phase II and Rabbit Lake type tailings.

Sulphide oxidation in surface deposits cannot be prevented but it can be greatly curtailed. Remedial measures include pyrite removal, flooding, soil cover and adding limestone. Both pyrite removal and flooding may be effective control methods. Limestone addition and soil cover are directed more towards reducing the rate of oxidation.

3.2.4 MAJOR CONTAMINANTS

There are numerous non-radiological contaminants in uranium tailings which can be measured in runoff and seepage. These include heavy metals, transition elements, rare earths, salts and nutrients. Elements common to many uranium tailings deposits include vanadium, cobalt, nickel, arsenic, strontium, yttrium and other rare earths, molybdenum, barium, lead and other common heavy metals. Virtually all of these elements are mobilized under acidic conditions and therefore may be present at undesirable levels in the discharges from acidic uranium tailings. Arsenic and nickel may be potential concerns especially in the high-grade deposits from the Athabasca Basin region. Typical levels in porewater runoff and seepage are presented in Table 3.2-3.

TABLE 3.2-3
TYPICAL LEVELS OF ARSENIC AND NICKEL IN URANIUM TAILINGS

	Low-Grade Ore Elliot Lake Tailings		High-Grade[1] Ore Saskatchewan Tailings	
	Arsenic	Nickel	Arsenic	Nickel
tailings solids (%)	<0.01	<0.01	1.5	2.0
tailings discharge (mg/l)	<0.1	<0.1	1-2	<0.1
seepage (long-term) (mg/l)	<0.1	0.1	2-10	1-10
metal mining effluent regulations (mg/l)	0.5	0.5	0.5	0.5

[1](From Knight and Piesold 1985, 1984)

Arsenic chemistry and mobility in Canadian uranium tailings have been studied (Knight and Piesold 1985, 1986, Beak 1986 and Melis 1986). It appears that arsenic dissolution is controlled by a complex mixture of metalloarsenates and the oxidation of arsenic-bearing sulphides. Geochemical modelling of arsenic based upon the predicted mineral composition of the tailings suggests that elevated levels of arsenic could occur in tailings seepages. It would appear that arsenic, from dissolved arsenate complexes, is readsorbed on the many metal hydroxides present. Both iron and aluminum hydroxide are known to adsorb arsenic. Knight and Piesold found that natural materials (sand) used in the construction of the Key Lake tailings repository had a large capacity to adsorb and retard arsenic migration. Long-term levels of arsenic in seepage from high-grade deposits are expected to be in the 2-10 mg/l range.

Nickel chemistry and mobility in Canadian uranium tailings have been studied (Knight and Piesold 1985, Beak 1986 and Melis 1986). Nickel solubility in uranium tailings from the Athabasca Basin region appears to be controlled by nickel hydroxide at pH levels above 8 and a complex nickel sulphate at levels below pH 8. For these tailings, if pH levels are maintained in the near neutral range, nickel solubility would be in the <1 to 10 mg/L range. If pH levels were to drop below 6.0 elevated levels of nickel are expected.

3.2.5 CHEMICAL PRECIPITATES

The uranium content of most ores represents a small fraction of the total ore weight and typically ranges from 0.1 percent in low-grade deposits to 2.0 percent or higher in high-grade deposits. Processing chemicals used in milling contribute to both the total weight and volume of tailings produced. The primary contributor is gypsum which forms upon neutralization of the sulphuric acid leaching solution with limestone or lime. Other precipitates of aluminum and iron may also contribute to increased weight.

A standard low-grade uranium tailings has a weight increase of 6.5 percent and a tailings dry density of 1.3 tonnes/m^3, (SENES 1986a). Therefore, one tonne of low-grade uranium ore produces 0.82 m^3 of tailings. Similarily, the high-grade uranium tailings exhibit a weight increase from milling of 20 percent or more. At a tailings dry density of 0.7 tonnes/m^3, one tonne of high-grade ore produces 1.7 m^3 of tailings.

The measured in situ density of uranium tailings is low by comparison with typical base metal tailings. A typical tailings repository from a flotation hydrometallurgical process would contain 1.5 tonnes/m^3. As discussed above, measured dry densities range from 0.7 to 1.3 tonnes/m^3. This is believed to be due to several factors including the clay and precipitate content of the acid leach uranium tailings. Precipitates are difficult to dewater and hinder consolidation. Typically the higher the precipitate content, the lower the density. This is discussed in more detail in the evaluation of the generic wet tailings site, see Section 5.4.

Chemical precipitates may be responsible in part for controlling the rate of radionuclide migration and buffering acidic seepages. Their dissolution and migration from the tailings basin can impact the stability of construction materials. Redeposition can result in precipitates blocking drainage systems. The effects on radionuclide mobility are discussed in Section 3.2.6. Buffering reactions and stability effects are discussed below.

Ferric hydroxide and aluminum hydroxide are present in elevated levels in most uranium tailings (0.1 to 1 percent). Given the relative solubility of those minerals in the pH range of 3 to 5, the dissolution of these minerals will tend to control pH levels in acid producing tailings. Often, tailings porewater exhibits low pH in the near surface zones with increasing pH to the neutral range at depth. This is likely the result of carbonate and hydroxide reactions with hydrogen ion as porewater flows down through the pile.

A contentious property of salts such as calcium sulphate (gypsum) is their effect on natural soils and concrete structures. Gypsum is commonly used as a conditioner for clayey soils because it reacts with clay minerals and alters the grain structures. Calcium tends to be adsorbed causing the grains to shrink and the clay to become less plastic and more permeable. Because of the high gypsum content in uranium tailings, there is some concern over the effectiveness of clayey soils for the long-term containment of uranium tailings solutions. This concern is valid where the permeability of the clay liner is a key to the successful operations of the tailings repository.

Sulphates are also known to degrade concrete, and this could well affect the long-term stabilities of grout curtains, concrete walls, etc., (Clifton 1986). Sulphate may lead to accelerated deterioration of concrete, and calcium sulphate is known to cause major scaling problems, which tend to plug liners, foundations and drains and reduce the overall permeability of the structures. The prime reaction would include calcium carbonate precipitation from ground waters on exposure to elevated levels of calcium sulphate in tailings solutions or gypsum precipitation from super saturated solutions. Where the stability of embankments or control structures depends on drainage, blockage could result in failure of the control structure.

3.2.6 RADIOACTIVITY

The radioactive elements found in uranium tailings are present in all mine tailings. The difference is that concentrations are higher in uranium tailings than those normally found in other mine tailings. As the grade of the ore increases, the radiological concerns increase and the appropriate tailings disposal technology is modified to address these concerns. There are four concerns associated with the radioactive elements:

- elevated levels of gamma radiation
- release of airborne dust containing radionuclides
- release of radon gas, and
- migration of radionuclides in surface and groundwaters.

Each of these aspects is addressed below.

3.2.6.1 Gamma Radiation

Surface gamma radiation is primarily a function of specific activity of radium in the tailings, the water content and the density of the tailings. Many models are available to predict both surface activity as well as the effect of cover on shielding the activity. Surface gamma levels at uranium tailings sites vary from <2 μSv/h on coarse beaches at Elliot Lake to more than 60 μSv/h on thickened Key Lake tailings. The necessity for gamma radiation control is normally determined through a radiological pathways analysis. Modelling performed for Beaverlodge tailings indicates that the direct gamma radiation exposure without shielding (cover) represents only a small percentage of the dose commitment to the local receptors, (SENES 1983). This assumes that the receptors spend a trivial amount of time in the vicinity of the tailings areas. For example, the highest direct radiation dose to a critical receptor from the Fookes and Marie lake uranium tailings area at Beaverlodge was estimated to be 0.01 mSv/yr, (SENES 1983). This compares with the long-term public dose limit of 5 μSv/yr.

3.2.6.2 Airborne Dust

Airborne dust from uranium tailings is a potential pathway for radionuclide release. Processing of uranium ores tends to concentrate both radium and thorium in fine fractions of the tailings, increasing the specific activity of the suspendable particulate. This is neither a major short or long-term concern providing measures for dust control are in place. Airborne releases can result in radiological dose to people by direct inhalation, groundshine from deposited dust and through uptake by plants, vegetables and animals. Vegetation will greatly reduce dust and cover will essentially eliminate these emissions. For example, the airborne dust pathway for the vegetated Fookes and Marie Lake tailings areas at Beaverlodge is predicted to contribute 0.005 mSv/yr to the critical receptor.

3.2.6.3 Radon

Radon-222 is ubiquitous in the environment. Numerous studies have been conducted on radon emanation and ambient radon levels both on and around Canadian uranium tailings basins. Radon emanation from tailings depends upon radium content, moisture content, depth of the deposit, emanating power, particle size distribution and porosity. Under normal conditions radon control is not a consideration during tailings deposition, however, it may be appropriate for long-term management. Cover technology for radon control is highly advanced and several models including RAECOM, (Rogers et al 1984) are available for use in their design. For the low-grade deposits decommissioned in Canada no radon control technology has been required. For high-grade deposits, covers have been proposed.

The radon pathway is a primary concern in the United States. In Canada, this pathway is typically a more minor component of the overall dose commitment. The uranium mining areas of the midwest United States are arid and as such the non-operating tailings basins are very dry. This leads to very high radon emission rates in comparison with Canadian tailings which typically have much higher moisture contents. As moisture levels increase, radon emissions are greatly reduced. Radon emanation rates are highly variable. Typical levels for low-grade tailings are 1-5 $Bq/m^2/s$ and for high-grade tailings 1 to 60 $Bq/m^2/s$ (see Section 7.4). Winter rates of radon emissions with frozen soil and snow cover are often negligible leading to very low annual averages even at high-grade tailings sites.

For the Beaverlodge decommissioning the measured dose from radon was small. The predicted dose from the vegetated tailings area measured at the critical receptor was less than 0.001 μSv/yr as compared to the long-term public exposure limit of 5 mSv/yr.

3.2.6.4 Waterborne Radionuclides

Uranium tailings contain many radioactive isotopes of which radium-226, thorium-230 and lead-210 are generally considered to be most significant. With uranium ore milling, 95% or more of the uranium is extracted from the tailings, but, most other nuclides are deposited with the tailings. Therefore, the parent to the uranium-238 chain is depleted but the daughter product concentrations remain elevated. Because elements such as thorium-230 have a radioactive half-life of approximately 80,000 years, the radioactivity in the tailings will persist for tens of thousands of years in the tailings basins. Leaching by infiltrating waters is one of the primary mechanisms for reducing the concentration of these elements in the tailings.

With sulphuric acid leaching, it is generally believed that upon the dissolution of uranium within the milling circuit, daughter products thorium-230, lead-210 and radium-226 are dissolved. Radium and lead subsequently precipitate as sulphates while thorium remains soluble until the pH is adjusted to above 4.0. At pH 4.0, the majority of thorium is precipitated as an oxide or hydroxide. Thorium may also be removed by co-precipitation with iron. Typical levels for radium-226, thorium isotopes and lead-210 in uranium tailings are summarized in Table 3.2-4.

TABLE 3.2-4
TYPICAL LEVELS OF RADIONUCLIDES IN TAILINGS SOLIDS AND POREWATER[1]

		Low-Grade Elliot Lake Ores (0.1% U_3O_8)		High-Grade Saskatchewan Ores (2.0% U_3O_8)	
	Tailings[2] Solids	Neutral Porewater	Acidic Porewater	Tailings Solids	Neutral Porewater
pH	-	7	2	-	7
Radium-226					
Bq/g	11	-	-	180	-
Bq/L	-	5-10	1-10	-	10-50
Total Thorium					
μg/g	230	-	-	170	-
μg/L	-	50	20,000	-	50
Thorium-230					
Bq/g	11	-	-	180	-
Bq/L	-	<1-10	>100	-	1
Lead-210					
Bq/g	11	-	-	180	-
Bq/L	-	1	50	-	0.5
Uranium					
μg/g	50	-	-	300	-
μg/L	-	<0.5	10	-	<0.1

[1] Based upon SENES 1986a

[2] Fresh Tailings - Acid Conditions may greatly reduce thorium levels in the solid tailings.

3.2.6.5 Radium

Radium chemistry in Canadian uranium deposits has been extensively reviewed by the NUTP, (Chemex 1986, Beak 1985, and SENES 1985). It has been generally accepted that radium contained in uranium tailings primarily occurs as a metallic sulphate co-precipitate. The primary metallic coprecipitates are believed to be barium, lead (and calcium). Therefore radium levels, unlike most metals, are not controlled by solution pH but rather by sulphate content. In addition, radium is readily adsorbed onto many natural materials with partitioning coefficients (K_D) typically ranging from tens to hundreds of mL/g. Therefore, radium dissolved from a co-precipitate may not necessarily occur in porewater but rather may in part be adsorbed back onto the tailings solids.

The tendency of radium to plate out on solid surfaces and be adsorbed by many soils is an especially important phenomenon when considering the migration of radium in tailings seepages. Canadian studies (Morin et al 1981) have demonstrated that even sands (which are not normally good cation adsorbers) at the Nordic tailings area have an excellent capacity to retard radium migration. For the Cluff Lake decommissioning, radium migration rates will be reduced to the point where radioactive decay will essentially reduce the highly elevated radium levels in seepage to concentrations acceptable for discharge (Meneley and Cherry 1986).

The long-term levels of radium expected in porewater are not well understood. Modelling based upon sulphate co-precipitate dissolution indicates that radium levels should be inversely proportional to sulphate concentrations. Although some limited evidence indicates this may occur, the wealth of data from long-term leaching studies with columns suggest the radium porewater concentrations will decrease with time as sulphate is depleted.

The importance of radium chemistry to tailings disposal technology relates to the control of radium levels in downstream water receptors. Where health and safety or environmental degradation may occur, specific control technologies to limit radium release may be warranted. Disposal technology for radium control starts with good site selection and includes engineering controls as required to mitigate downstream effects. Radium removal from tailings as a milling process has little merit.

Uranium tailings contain equilibrium levels of radium-226. Specific activities range from <10 Bq/L for some low-grade tailings to >200 Pci/S for high grade tailings. Tailings discharges typically contain 10 to 150 Bq/L of radium-226 before treatment, and <0.37 Bq/L after treatment. This compares with a drinking water maximum objective of 1 Bq/L.

3.2.6.6 Thorium

Thorium chemistry in Canadian uranium tailings deposits has been studied for NUTP (Melis 1986). This work has confirmed that a large percentage of both thorium-232 and thorium-230 are dissolved in the mill, and reprecipitated during neutralization as thorium oxide/hydroxide. Thorium may also be co-precipitated or adsorbed with ferric hydroxide. Thorium mobility is most significantly affected by solution pH. Sulphate complexes are also formed increasing thorium mobility at elevated sulphate levels.

Because thorium is a highly radiotoxic element, disposal technology needs to consider the geochemistry of thorium. This concern is primarily focussed toward acid generating tailings where pH levels will drop below about 4. Disposal technology directed towards controlling acid generation is directly applicable to controlling thorium. Milling technologies for reducing the thorium content of tailings are available but none have been applied as an environmental control practice. Thorium was recovered for a short time at Elliot Lake in the 1960's and stockpiled for future sale.

Uranium tailings typically contain equilibrium levels of thorium-230. However, thorium-232 contents are very site-specific. High-grade uranium ores such as those found at Key Lake contain 200 pCi/g of thorium-230 and 0.02% thorium-232 while the low-grade Elliot lake ores contain only 10 pCi/g thorium-230 and 0.025% thorium-232. Neutral tailings effluents for these areas typically contain <1 Bq/L of thorium-230 and <0.01 mg/L thorium-232. Acid seepages on the other hand can contain hundreds of Bq/L of thorium-230 and tens of mg/L of thorium-232.

Although there are no explicit drinking water criteria for thorium-230, the maximum acceptable concentration (MAC) based upon 1 percent of the ICRP annual exposure limit is 1.4 Bq/L. This compares with the radium MAC of 1 Bq/L for radium-226.

3.2.6.7 Lead

Very little direct work has been undertaken on the chemistry of lead-210 in Canadian uranium tailings piles. With sulphuric acid leaching, it is generally accepted that lead is dissolved in the milling circuit and reprecipitated from solution as lead sulphate. Lead sulphate solubility is then controlled by sulphate levels in the tailings. Unlike radium, lead solubility is a function of pH once dissolved from the lead sulphate complex. At neutral to alkaline pH levels, lead will reprecipitate as an hydroxide or carbonate mineral.

Lead-210 levels in tailings are highly variable and would appear to be independent of ore grade. Levels are typically reported in the 0.1 to 10 Bq/L range. Because of the short half-life of Pb-210 (22 years) lead-210 solubility in tailings may well be controlled by the ingrowth from radium-226 complexes. The MAC for lead-210 is 0.3 Bq/L compared with the radium-226 MAC of 1 Bq/L.

3.3 PHYSICAL CHARACTERISTICS - EFFECTS ON DISPOSAL TECHNOLOGY

There are several physical characteristics that influence the technology for the disposal of uranium tailings. The grain size distribution and the nature of the finer fraction (clay mineralogy) play an important part in determining these properties. They control the secondary properties such as:

- hydraulic conductivity which determines rate of consolidation, seepage and filterability (for dry tailings),
- initial settled density and hence impoundment storage capacity and consolidation settlement,
- frost susceptability and frost heave, and
- chemical composition of tailings fractions.

3.3.1 LOW-GRADE PYRITIC TAILINGS

Coarse grained tailings (+75 microns) typical of the Elliot Lake area tend to undergo substantial sand/slime separation upon deposition leaving sand beaches and slimes pools. Although thickening has been attempted, (Chakravatti et al 1982), no full-scale application of discharge thickened or tailings has been done.

Coarse tailings beaches have high densities, typically $>1.4\ t/m^3$. Slime pools have densities typically $<1.1\ t/m^3$. Coarse materials are well drained, well consolidated, readily trafficable, and not greatly affected by frost action. The fine tailings (minus 75 microns) have high water contents, low permeability, are unconsolidated, not readily trafficable and more subject to frost action.

The physical characteristics of the slime and sand fractions are also affected by minerological make-up. The fine fraction in uranium tailings tends to concentrate chemical precipitates which are gelatinous and do not readily settle.

The geotechnical and engineering properties of the Elliot Lake tailings have been reviewed (Beak and Golder Associates 1986) and these properties are summarized in Table 3.3-1.

The physical properties as discussed have several effects on disposal technology for these low-grade, coarse-grained materials. Some of the more pertinent effects are noted below:

- because of the coarse nature, tailings tend to segregate readily. Methods are currently not available to pump tailings at a sufficient solids content to prevent segregation,
- the formation of sand beaches has been used to advantage for the recovery of sands for dam and dyke construction,
- cover application over coarse material is readily achieved. Compression indices for slimes ranging from 0.2 to 0.45 (Matyas et al 1984) indicating that appreciable consolidation will occur on placing a cover. Although this does not preclude cover application it may impact upon the cost and the long-term competence of the cover especially where large differential settlements may occur.

TABLE 3.3-1
ELLIOT LAKE TAILINGS CHARACTERISTICS

	Slimes	Sands
Geotechnical and Engineering Properties		
I. Index Properties		
Grain Size	silt with some sand (1-400 μm)	fine-medium sand, silty sand (60-10,000 μm)
Plasticity (average)	non-plastic	non-plastic
- Liquid Limit (%)	33	-
- Plastic Limit (%)	31	-
- Plasticity Index(%)	2	-
Specific Gravity (g/cm^3)	2.67	2.73
II. In Situ Properties		
Water Content (%)		
- Surface	100 to 105	35
- Deep (12m)	30 to 50	30
In Situ Density (t/m^3)		
Void Ratio		
- Surface	3.6	1.5
- Deep (15 m)	1.5	0.70
Dry Density		
- Surface	0.64	1.21
- Deep (15 m)	1.04	1.6
Relative Density (%)		
- Above Water Table	-	30 to 100
- Below Water Table	0 to 50	0 to 70
III. Engineering Properties		
Permeability (m/s)		
- Laboratory	10^{-7} to 10^{-8}	10^{-5} to 10^{-6}
- Field	$3x10^{-5}$ to $3x10^{-6}$	10^{-4} to $3x10^{-7}$
Compression Index	0.2 to 0.45	0.04 to 0.1
Coefficient of Consolidation (m^2/yr)	1.6 to 6.3	63 to 630
Drained Shear Strength	36° to 46°	30° to 41°
Undrained Shear Strength (kPa)		
- Surface	-	-
- Deep (3 m)	4.8 to 14.4	-

(Adapted from Beak and Golder 1986)

- fine tailings have low permeabilities and are difficult to dewater as is evidenced by the high water contents and excess pore pressures in slime tailings, even under several metres of tailings. This does not greatly impact on the disposal method selected. Where appropriate, underdrains could be employed to promote consolidation. As a general rule, elevated water tables are preferable in acid generating tailings in order to reduce the rate of pyrite oxidation. Therefore, containment in rock-rimmed valleys where seepage rates are low and water tables are elevated is typically the preferred disposal technology.

- Adoption of tailings placement systems which either minimize segregation or produce successive thin layers of coarse and fine tailings and dewater or drain more rapidly resulting in more uniform deposits. Uniform consolidation and strength characteristics may be advantageous for placing and maintaining covers.

3.3.2 LOW-GRADE, NON-PYRITIC TAILINGS

Low-grade, non-pyritic tailings at Rabbit Lake, Bancroft and Beaverlodge have characteristics similar to the pyritic tailings. Dry tailings densities are very site-specific and range from <1 t/m^3 at Rabbit Lake, (MacLaren 1985) to 1.5 t/m^3 at Beaverlodge. Beaverlodge tailings are finer than other low-grade uranium tailings since the sands were extracted and used as underground backfill.

3.3.3 HIGH-GRADE SASKATCHEWAN TAILINGS

The high-grade Saskatchewan tailings are fine-grained and typically contain 75% minus 75 micron particles. Much of this fine material results from the precipitation of gypsum and metal hydroxides. These hydroxide solids are unstable under consolidation stresses resulting in long-term secondary consolidation due to recrystalization. Because of the very fine nature of these tailings they tend to exhibit slurry behaviour at low solids densities (30% solids) and they do not consolidate well. Unweathered tailings have measured hydraulic conductivities in the range of 10^{-8} m/s and remain in a semi-fluid, supersaturated state until some external force is applied to promote secondary consolidation, (Knight and Piesold 1979).

There are little data available on the physical properties of these high-grade tailings. Table 3.3-2 summarizes data for Rabbit Lake tailings. Experience has demonstrated that these materials are unusual and significantly affected by frost action. Even with underdrainage systems and the use of layered placement techniques for deposition, in place dry densities are very low. Data collected for the Key Lake tailings (Knight and Piesold 1985) indicate the dry densities of the tailings averages 0.64 t/m^3 with measurements ranging from from 0.33 to 1.44 t/m^3.

TABLE 3.3-2
RABBIT LAKE TAILINGS CHARACTERISTICS

Grain Size	silts, clayey silts and silty sands
Plasticity of silts (average)	
- Liquid Limit (%)	67
- Plastic Limit (%)	49
- Plasticity Index (%)	18
Specific gravity (g/cm^3)	2.6 to 2.8
Void ratios	
- Surface	4.5 - 5.5
- Deep (15 m)	1.2 - 2.3
Water Contents (%)	87 - 216
Permeability (m/s)	
- Silts and clayey silts	1×10^{-7}
- Silty sands	1×10^{-6} to 2×10^{-5}
Compression Index	0.53 to 0.81
Coefficient of Consolidation (m^2/yr)	126 to 630
Undrained Shear Strength (kPa)	
- 4 m deep	5 to 15
Drained Shear Strength	35° to 37° (14 kPa cohesion)

Typical of 'wet' tailings, adapted from Rabbit Lake data (after Gulf Minerals Canada 1981, MacLaren Engineers 1984, and Geocon 1986).

Frost action appears to have a major effect on fine-grained tailings. Fresh dewatered tailings are very clay-like and impermeable, while frozen tailings have a crystalline honeycomb type appearance with much higher permeabilities. Upon freezing and thawing, porewaters are released and the density would also appear to increase. The physical properties and long-term behaviour of these tailings are still very poorly understood.

Because of the unique nature of these tailings it is likely that some form of positive drainage (under drains, internal drainage layers, etc.) must be employed to ensure that tailings can be consolidated. Given the highly porous nature (75 percent porosity) of the dry tailings a significant additional consolidation can be expected after close-out. Long-term secondary consolidation (after dissipation of pore pressures) is also anticipated. Much of this settlement may occur after cover application and this potential consolidation should be considered in the overall cover design and application.

3.4 EFFECTS OF SITE CHARACTERISTICS ON DISPOSAL TECHNOLOGY

3.4.1 DEMOGRAPHY

The uranium mining regions are on the Canadian Shield in areas with low population density. Population centres are often arise as result of the presence of the mines; therefore, as the mines are decommissioned, regional populations decline. Because of this isolation, population doses and the resultant risks from decommissioned sites are typically very low. This is especially true in the remote mining regions of northern Saskatchewan. For example, in the area of Beaverlodge Mine in northern Saskatchewan, the closest population centre is Uranium City. This town had a population in the 3,000 to 5,000 range during mining, but it has declined to less than 300 since closure. Therefore the regional population which could be affected by radioactivity is small. In fact, (SENES 1983), calculated a collective population dose of 0.07 man-sieverts/yr. Using the value of $10,000/man-sievert, this translates to $7000/yr that could be justified on reclamation to eliminate the dose. Given that reclamation costs are typically in the millions of dollars, no reclamation works could be justified on a radiological protection basis. If this mine was in a populated area, reclamation alternatives to reduce the dose might have been justifiable.

3.4.2 TOPOGRAPHY AND GEOLOGY

Topography plays a major role in the siting of a uranium tailings area but a lesser role in determining the disposal technology applied at the site. For example, while areas containing large valleys and lake basins are most suited to natural containment systems, the topography does not preclude the use of liners, underdrains, engineered barriers, etc., at the disposal point. Advantage can be taken of the natural topographic features by an appropriate process of site selection at the time of impoundment design.

In Canada, the two prime uranium mining areas are in the Canadian Shield, where topography is well suited to tailings containment. The Elliot Lake area has minimal overburden with large rock rimmed valleys and lake basins. These basins are ideal for containing the large quantities of low-grade uranium tailings. The natural rock rims provide both long-term, stable containment structures and natural protection from wind and water erosion.

The geology of the area plays a significant role in applicable disposal technology. The local rock has low permeability and provides for minimal seepage except in the outwash valleys which are typically in-filled with sands and glacial till. The relative shortage of construction materials (sands, gravels and tills) dictates that embankment volumes are modest. It also precludes the application of deep covers at close-out as suitable low-permeability cover materials are not readily available. Other mining operations in the Shield often use tailings for dam construction. This is especially common for gold mining operations. Use of tailing for construction of outer perimeter dikes is generally considered suitable for uranium tailings only if used in the upstream shell of an impervious dam.

In northern Saskatchewan the high-grade uranium mining properties are in undulating topography. Although overburden depths are not great, there are typically adequate quantities of dam construction materials. Because tailings volumes are small in comparison with the low-grade tailings there is no need to use large lake basins for containment. This does not preclude the use of these basins as they often provide the best contaminant systems available at a given site.

The low-grade uranium mining regions in northern Saskatchewan (Gunnar, Lorado, Beaverlodge) are topographically and geologically similar to the Elliot Lake region. Overburden depths are minimal and lake basins are more predominant than in the high-grade mining areas.

3.4.3 SEISMICITY

Seismicity subjects the structures and tailings to dynamic loads. All the abandoned and producing uranium mines are in areas of low seismicity. Concerns regarding seismic loadings and effects would be greater for impoundments that may be constructed in the future in more active seismic areas of Canada. Design and construction procedures are, however, well developed to withstand seismic loadings (ASCE 1982).

3.4.4 GEOHYDROLOGY/GEOCHEMISTRY

The geohydrology of an area is perhaps the most important factor affecting the tailings disposal technology applicable at a site. The geohydrology will determine seepage rates, rate of radionuclide migration, the direction of seepage flow, and ultimately could determine the long-term effectiveness of the closed-out facility.

In the selection of the tailings disposal area, geohydrology will often dictate whether a liner is necessary, underdrains are required, long-term seepage collection and treatment is necessary, etc. The requirements are highly site and tailings specific.

Liners are normally applied when the permeability of the natural rock or soil foundations under a tailings repository is unacceptable. In Canada, synthetic liners have never been used to line a tailings area and only one tailings area has been lined with bentonite modified till. This is not to say that all sites have impermeable foundations. Many areas do contain highly pervious windows in the overburden soils; however, seepage from these areas is normally managed with cutoff walls to bedrock beneath the perimeter dams. Pervious soils can act as underdrains and as natural geochemical barriers to retard contamination. In at least one instance, a uranium tailings area was founded on pervious sands, peat, and till with the intent over the long-term of allowing infiltration to exit the site as seepage. The migration rate of radionuclides (radium) from the site is very low so that virtually all radium decays before reaching the downstream receptor.

Radionuclides may be attenuated by bedrock. The efficiency of the attenuation depends upon the length of the flow path, the adsorptive surface area in the fractures and the mineralogy of the precipitates and gangue within the fractures. Geochemical reactions between seepage water and the local groundwaters can also result in precipitation of various compounds including metals, radionuclides and calcite.

3.4.5 CLIMATIC CONDITIONS

The climate of an area can greatly affect disposal technology. The more important factors include temperature, annual rainfall and storm events.

Temperature in areas such as northern Saskatchewan control frost action and permafrost. Both frost action and permafrost affect the integrity of a closed-out tailings facility. For example, frost action can weather covers and this leads to increased infiltration and erosion.

The effects of frozen tailings on the long-term integrity of a facility are not well understood. It is possible that large blocks of permafrost within a closed-out facility could thaw and cause major settling which could affect the competence of the cover. Conversely, frost action and freezing increases the permeability of tailings and this can be used to improve tailings dewatering and consolidation. Permafrost conditions would prevent infiltration and therefore long-term seepage from the base of the impoundment.

In the cold climate of northern Saskatchewan, unique problems such as glaciation in surface drainages can occur. Ice accumulates in ditches and channels which, if not maintained, can produce serious environmental consequences, see Section 8.3.

3.4.6 HYDROLOGY

The annual rainfall affects the amount of runoff, the need for diversion works, the size of the treatment plant, and can impact both wind and water erosion. In Canadian uranium mining districts, there is generally a net water surplus and consequently water management is normally a major concern. Conversely, wind erosion is a secondary concern as tailings tend to have high water contents thus reducing the dusting potential. Increased moisture content in the surficial tailings layers also helps to suppress radon exhalation. With excess rainfall, surface stabilization with vegetation is normally readily achieved.

Extreme rainfall events have a large effect on the design of a containment facility. Because the tailings and effluents, are contaminated, regulatory agencies normally require all storm waters to be intercepted and treated before discharge. For most tailings areas, this can be achieved, however major efforts are often required to maximize the amount of fresh water diverted from the site. To limit the quantity of water which must be diverted or treated it is normally desirable to select a site with a small catchment area. Because of the complex, poorly developed drainage systems on the Canadian Shield, this is generally easily achieved. Diversion of large flows requires major erosion protection works and a requirement for long-term maintenance.

The waters of mining regions in Ontario and Saskatchewan are very soft, have a minimal dissolved ion content and are poorly buffered. Therefore, the natural receiving water body quality can be easily modified. The reasonably high dilution available in the regional watersheds can mitigate many effects but where high densities of mining activity occurs, water quality has suffered unless properly treated.

3.4.7 VEGETATION

Vegetation can be successfully applied at Canadian uranium mining areas if the tails are amended to produce suitable growing conditions as there is adequate precipitation to support a healthy vegetative cover. Forest cover can be expected as it is present in all regions. Therefore the use of vegetation to stabilize surfaces and reduce wind and water erosion is a feasible abandonment treatment, see Photo 3.4-1.

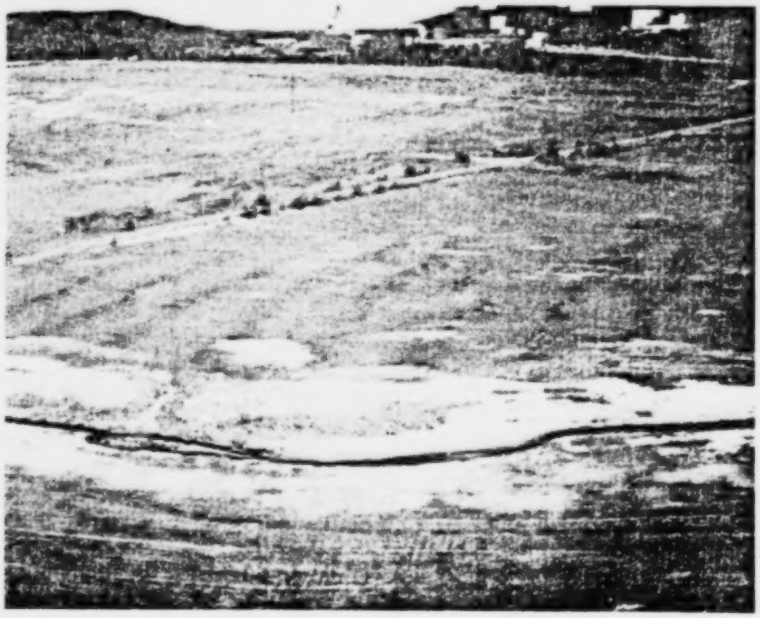


Photo 3.4-1 Vegetated tailings Nordic Mine, Elliot Lake, Ontario. Drainage ditch for acid water in foreground.

3.4.8 MAMMALS

There are several mammals at uranium mining areas that can affect the successful operation of a closed-out tailings areas. Burrowing animals, including rabbits and woodchucks, can penetrate covers, bring tailings to the surface and provide access holes for both water infiltration and radon release. Of more significance is beaver activity which can plug decants, discharge and diversion channels. If diversion channels fail, more water will enter the tailings basin. If decants or spillways are blocked, there is a potential for a dam overtopping which could produce a catastrophic failure.

3.5 CANADIAN CASE HISTORIES ON DECOMMISSIONING

3.5.1 GENERAL

Since 1980, three uranium mining operations have been fully decommissioned and the sites reclaimed. These properties are the Beaverlodge mine in northern Saskatchewan, the Agnew Lake mine near Espanola, Ontario and the Faraday mine near Bancroft, Ontario. The decommissioning of each property has proceeded in a timely fashion with excellent results so far. This is particularly meritorious since no specific closeout requirements have been established by the regulatory authorities. Each property is very different and several regulatory jurisdictions were involved with the negotiations leading to the "successful" reclamation plans. None have gone long enough to claim success.

A brief review of the highlights of the operating phase, the decommissioning and reclamation plans and the progress and success of implementation is reviewed in the following sections.

3.5.2 BEAVERLODGE MINE

Uranium mining of the pitchblende deposits in the vicinity of the "St. Louis Fault" began in 1950. Milling at Beaverlodge commenced in 1953 and continued until June 1982. Over that period, more than 10 million kg of U_3O_8 were produced. The milling circuit employed carbonate leaching although a small acid leach circuit was used to treat a pyrite flotation concentrate sidestream. Over the 29-year operating period 10.1 million tonnes of tailings were produced of which 4.3 million tonnes of coarse material were used as mine backfill and 5.9 million tonnes were sent to the tailings impoundment, (MacLaren 1983). At completion of the operation, the following disturbed areas were in place, see (Eldorado 1983), as shown on Figure 3.5-1.

- three separate tailings disposal areas in Mine Water Lake, Marie Lake and Fookes Lake,
- tailings spills along the tailings pipeline corridors and within the Ace Creek floodplain,
- thirteen waste rock areas covering 54 ha and containing 4.8 million tonnes of rock,
- fourteen mining locations which include ten shafts and adits and fourteen open pits,
- numerous mining, milling, and support buildings, and
- a townsite.

In the development of the decommissioning plan, Eldorado Resources decided that the Beaverlodge mine would never reopen, therefore, a primary objective was complete abandonment of the site. To meet this objective, Eldorado negotiated the close-out plan with the regulatory bodies, (MacLaren 1983, SRK 1983, SENES 1983). Supporting studies included extensive environmental background monitoring, engineering design, environmental modelling and pathways analyses and ALARA optimization analyses. The end result was a mutually acceptable plan which set target objectives which, if met, would permit Eldorado to abandon the site.

The basic plan involved:

- salvage of saleable equipment and some buildings,
- demolition or burial of all buildings including the mine and mill structures,
- removal of tailings in the Ace Creek flood plain and Minewater lake with disposal in the mine or Marie Lake,

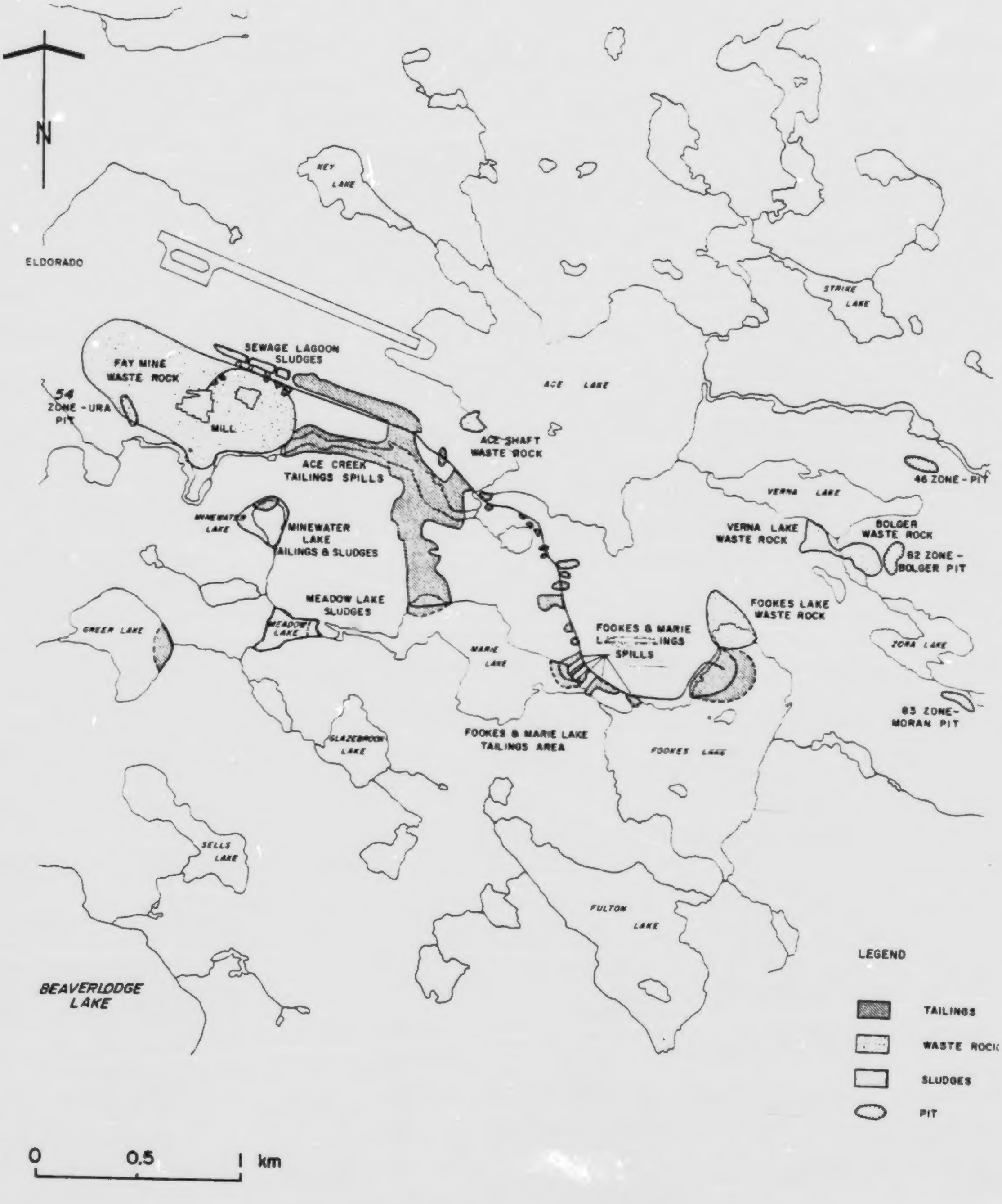

N
KEY LAKE
ELDORADO
STRIKE LAKE
ACE LAKE
SEWAGE LAGOON SLUDGES
FAY MINE WASTE ROCK
54 ZONE - URA PIT
MILL
ACE SHAFT WASTE ROCK
ACE CREEK TAILINGS SPILLS
46 ZONE - PIT
VERNA LAKE
MINEWATER LAKE
MINEWATER LAKE TAILINGS & SLUDGES
VERNA LAKE WASTE ROCK
BOLGER WASTE ROCK
82 ZONE - BOLGER PIT
MEADOW LAKE SLUDGES
FOOKES LAKE WASTE ROCK
GREER LAKE
MEADOW LAKE
FOOKES & MARIE LAKE TAILINGS SPILLS
MARIE LAKE
ZORA LAKE
83 ZONE- MORAN PIT
GLAZEBROOK LAKE
FOOKES & MARIE LAKE TAILINGS AREA
FOOKES LAKE
SELLS LAKE
FULTON LAKE
BEAVERLODGE LAKE
LEGEND
TAILINGS
WASTE ROCK
SLUDGES
PIT
0
0.5
1 km

Figure 3.5-1 Beaverlodge Mine Major Waste Areas

- covering of tailings beaches with waste rock (if not under water),
- general grading of waste rock areas,
- sealing of all shafts and adits and in filling of small pits, and
- disposal of mill solutions in the mine.

Each of these items is briefly reviewed below.

Wherever practicable, buildings and equipment that could be decontaminated and potentially sold at a profit were removed from the site. With the inactivity in the mining industry, much of the equipment salvaged is still in storage.

Demolition of the buildings was undertaken to ensure the site was safe, discourage people from living close to the tailings area and to return the site to an appearance which is similar to the surrounding environment. Demolition waste was buried within the waste rock dumps and some was trucked for disposal to the tailings basin. The mill buildings were buried by removing the roof and pushing waste from surrounding waste rock dumps in through the openings. Recent pictures of the mine/mill site show little evidence of the former mining operations.

Tailings in Minewater Lake and along the Ace Creek floodplain were removed and dumped into the mines. This work was conducted, to reclaim Minewater Lake and to remove tailings which could be eroded by Ace Creek. Tailings from these excavations were disposed in the mine shaft and in the tailings basin. Much of the excavation was conducted in the winter so that the foundations were stable enough to permit vehicular access. Neither the tailings spilled in Ace Creek or contained in Minewater Lake were a major source of contaminants to Beaverlodge Lake, (SENES 1983). Therefore, their removal has had minimal effect on water quality. In fact, as predicted, the removal of tailings from Minewater Lake has not greatly reduced the radionuclide content of the waters. This is because residual tailings in the watershed are still contributing contamination to the water.

The exposed tailings beaches were either moved to below the water line in the lakes or covered with waste rock. The purpose of the reclamation activity was to minimize surface erosion and to reduce surface gamma levels. This was successfully achieved; however, it was not a requirement as the radiological doses from both direct radiation and dust were very low, see (SENES 1983).

Where appropriate, waste rock areas were graded to stabilize side slopes and improve drainage. In selected cases waste rock was used to fill in small pits and cover exposed tailings. Again, these reclamation activities had minimal environmental consequence, but improved appearances.

All mine shaft and adits were sealed to ensure the site was safe and secure.

In summary, virtually all these actions were based upon good engineering principles to ensure long-term safety and stability of the site. No action was taken on the basis of radiological detriment. Pathways analyses demonstrated that critical doses to the public were minimal.

Monitoring during the transition phase is continuing and results to date are below the levels predicted in the model assessment. Of the nuclides present, uranium levels remain elevated as expected in the tailings discharge and radium levels are currently below drinking water standards. Eldorado hopes to transfer ownership of the property back to the province of Saskatchewan within the next few years.

3.5.3 AGNEW LAKE MINE

The Agnew Lake mine/mill complex was in Hyman Township about 50 km west of Sudbury, and 25 km northwest of Nairn Centre, Ontario.

The mine was unique in Canada in that the uranium was extracted directly from broken ore without grinding and extensive chemical processing typically used at uranium mining/milling operations. Leaching of the uranium was accomplished in underground stopes and on ore brought to the surface, by flooding or spraying the ore with acidic solutions (pH = 1.5) which dissolved the uranium. This is commonly referred to as underground leaching when done in the mining stopes, and heap leaching when undertaken on ore brought to the surface, (SENES 1982). The solutions bearing dissolved uranium are collected and sent to the uranium recovery plant. Therefore the mill does not produce a ground rock tailings but rather neutralized barren solution constitutes the "tailings" material. The tailings at Agnew Lake were pumped to a valley dam waste management area where the gypsum and metal hydroxide solids settled and the effluent was discharged into an adjoining polishing pond. The flow from the polishing pond was discharged seasonally.

The primary areas disturbed by mining activities, as shown on Figure 3.5-2, include:

- barren waste rock leach piles,
- residue tailings pond and polishing pond,
- mine openings, and
- mine/mill complex buildings.

Agnew Lake Mines determined that there was no future development potential for the mill, and therefore the decommissioning objective for the facility was to abandon the site. Agnew Lake Mines negotiated a decommissioning plan with the regulatory bodies to accomplish this end. Environmental modelling and pathways analysis were conducted to support the proposed plan, (SENES 1982).

The highlights of the plan were to:

- recover salvageable equipment,
- demolish all buildings,
- seal mine openings,
- relocate the heap leach piles to the tailings area,
- mix the tailings residues with rock to produce an impervious mass, and
- grade, shape, and vegetate the area to promote runoff and minimize seepage.

The plan has been fully implemented and all objectives of the plan have been met, (Zgola, 1986 and Lahaye 1986). Seepage flows from the reclaimed area are low. Water quality in the receiving stream meets all water quality objectives. Again, as with Beaverlodge, no specific actions were taken which can be related directly to the radioactivity of the waste materials. The plan simply applied good engineering principles.

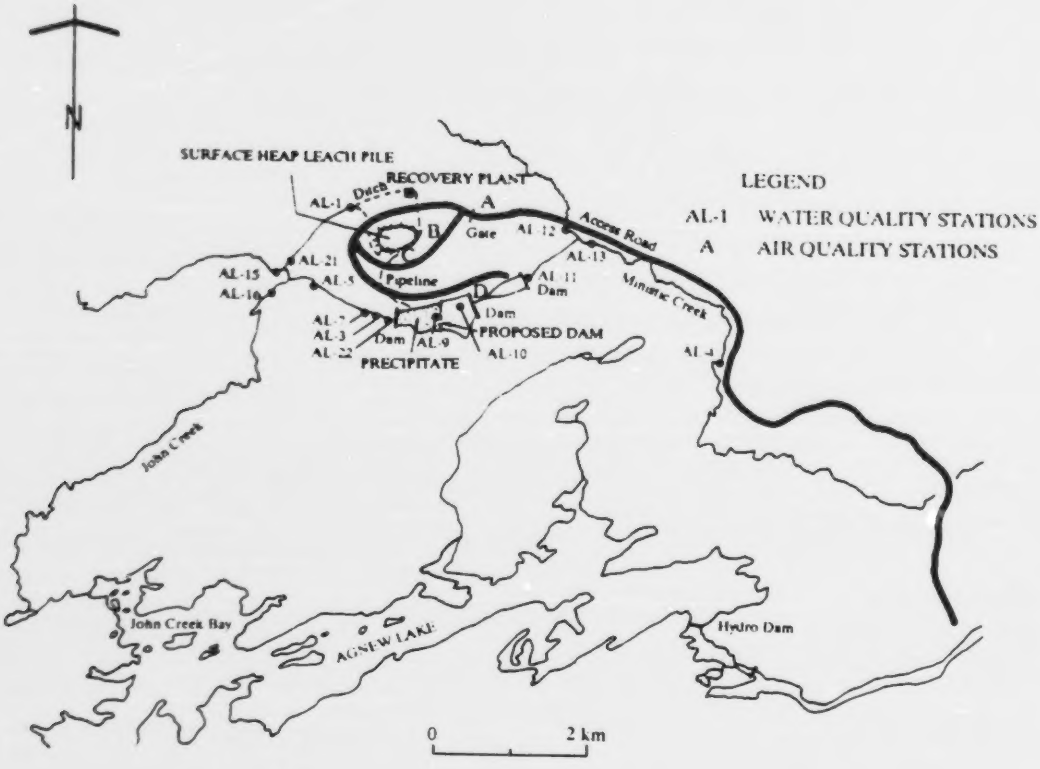

N
SURFACE HEAP LEACH PILE
RECOVERY PLANT
Ditch
AL-1
A
B
Gate
AL-12
Access Road
AL-13
AL-21
AL-15
AL-16
AL-5
Pipeline
AL-11
Dam
D
Minnitic Creek
AL-7
AL-3
AL-22
Dam
AL-9
Dam
PROPOSED DAM
AL-10
PRECIPITATE
AL-4
John Creek
John Creek Bay
AGNEW LAKE
Hydro Dam
0
2 km
LEGEND
AL-1 WATER QUALITY STATIONS
A AIR QUALITY STATIONS

Figure 3.5-2 Major Surfaces Facilities for Agnew Lake Mines

3.5.4 FARADAY MINE

The original proposal for decommissioning (Lendrum 1983), assumed that the mill and mine would be reactivated. This was modified when it became apparent that the mine would not reopen in the forseeable future. The decommissioning of the property is almost complete and has included:

- salvaging of all saleable equipment,
- general grading of the old tailings,
- covering of the new tailings area with rock and gravel, with grading and drainage improvements,
- demolition of the mine/mill building,
- sealing of mine openings, and
- monitoring the site.

The reclamation has gone well and water quality downstream is good. The Ontario Ministry of Environment have taken over the routine environmental monitoring as part of their overall provincial water quality monitoring programs.

CHAPTER 4
OBJECTIVES OF DISPOSAL TECHNOLOGY

The close-out criteria and objectives as defined by the regulatory authorities in Canada, and reviewed in Chapter 3, are cast in very broad terms of health, safety and long-term liability. For the definition of appropriate evaluation and design technology, it is necessary to establish more fully and precisely the factors that will determine or influence the parameters which are used in the assessment of whether the criteria and objectives are and will be achieved. This chapter reviews the factors that control mill waste containment and the manner in which they determine containment or release are discussed. Technology for release rate determination is briefly outlined and methods for release rate control briefly reviewed. The objectives for mill waste containment technology are defined in terms which relate to the release mechanisms, the control methods and the close-out criteria and objectives.

4.1 GENERAL

4.1.1 CONTAMINANT RELEASE CONTROL AND PATHWAYS

The objective of disposal technologies is to control contaminant releases from a tailings area to an acceptable level. This acceptable level is one which:

- meets a regulatory criteria or objectives,
- ensures public health and safety,
- minimizes environmental effects, and
- controls releases to ALARA levels.

Contaminant release control must be effective, not only at the time of abandonment of the tailings area but also for a long period thereafter. Long-term security of containment can be provided by either constructing containment facilities with long-term stability or by providing maintenance.

The Canadian regulatory approach is very flexible with few specific criteria, allowing for many control technologies to be applied to meet the short and long term objectives. For a uranium tailings area the primary contaminant and contaminant release mechanisms are:

- direct radiation,
- air emissions - radon and particulates,
- surface water - stormwater, dissolved and suspended contaminants,
- subsurface seepage - dissolved contaminants,
- acid generation - acidity and dissolved metals, and
- major containment failures - tailings.

These pathways are illustrated in Figure 4.1-1.

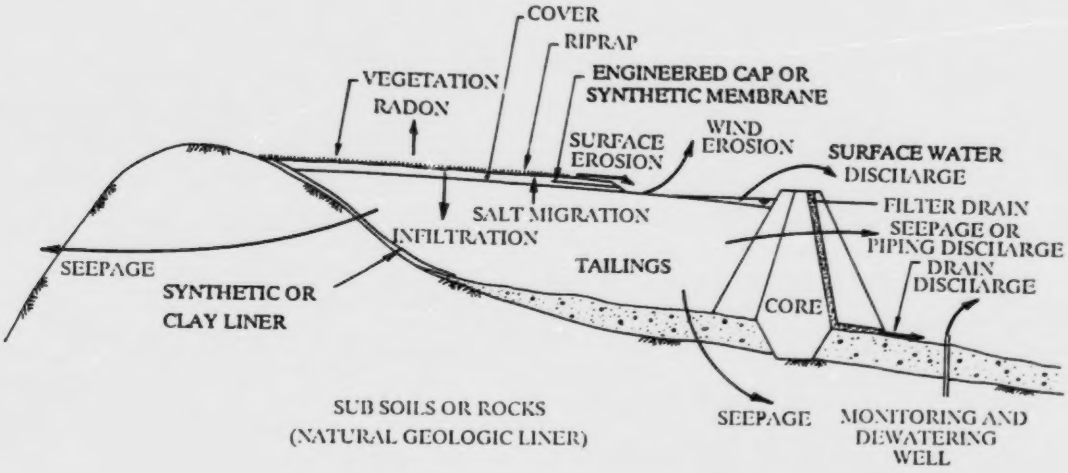

COVER
RIPRAP
ENGINEERED CAP OR SYNTHETIC MEMBRANE
VEGETATION
RADON
SURFACE EROSION
WIND EROSION
SURFACE WATER DISCHARGE
FILTER DRAIN
SALT MIGRATION
INFILTRATION
SEEPAGE OR PIPING DISCHARGE
DRAIN DISCHARGE
SEEPAGE
SYNTHETIC OR CLAY LINER
TAILINGS
CORE
SUB SOILS OR ROCKS (NATURAL GEOLOGIC LINER)
SEEPAGE
MONITORING AND DEWATERING WELL

Figure 4.1-1 Engineered Controls for Contaminant Releases from a Uranium Tailings Facility

This chapter briefly outlines:

- the control methods for mitigating the contaminant releases,
- summarizes the objective for each control method,
- summarizes the relevant short and long-term criteria for the control of the contaminant releases, and
- directs the reader to the appropriate section of the manual where the control methods and technologies are reviewed.

Table 4.1-1 provides a summary of the contaminant releases, control methods, technologies, objectives and criteria for the relevant disposal technologies.

4.1.2 PERIOD FOR WHICH TECHNOLOGY SHOULD BE EFFECTIVE

In common with approaches in the U.S.A. and Australia a period of 200 years is selected as the period for which it is considered technically feasible to achieve stability of most appropriately designed tailings containment structures. Since the period of concern applicable to the tailings extends well beyond this period, a period of 1000 to 2000 years is selected as the period for which the potential of appropriate technology should be evaluated.

In summary, the objective of the disposal technology is to provide control of contaminant releases for periods of at least 200 years and where practical for periods of 1000 to 2000 years.

4.1.3 PROVISION FOR SURVEILLANCE AND MAINTENANCE

Current technology is inadequate in certain areas of contaminant control to enable the construction of control structures that can function for the objective periods without a minimal amount of maintenance. Often the design and construction requirements to achieve such long-term stability are extremely onerous and costly and are not consistent with ALARA principles. An extreme example is the maintenance of a long-term water treatment facility. A more typical example is the prevention of severe gulley erosion in embankments.

Surveillance and maintenance is considered an essential and integral part in the assessment of the suitability of alternative control technologies, but the amount of maintenance that is appropriate should satisfy ALARA.

4.2 DIRECT RADIATION

Direct radiation levels are a function of ore grade. The common control methods are shielding and isolation. Shielding requirements can be readily evaluated by a simple radiation shielding analysis. Isolation can be provided by institutional controls. The primary objective for direct radiation control is to ensure that worker and public radiation dose limits are not exceeded. Direct radiation is only one source of radioactivity which must be included in the annual dose limits of 50 mSv and 5 mSv for radiation workers and members of the public. Once this is ensured, the need for additional controls can be assessed through a radiation pathways analysis. From the pathways analysis, the cover characteristics for shielding and/or the size of the isolation zone (zone under institutional control) can be determined.

Control technologies for gamma radiation are briefly discussed in Section 7.4 on radon control.

4.3 AIR EMISSIONS

4.3.1 RADON RELEASE

Radon release is a function of many parameters including ore grade, tailings depth, moisture content, porosity, density and grade of the tailings deposit. Where moisture levels are high, diffusion rates are greatly reduced and much of the radon decays before emanating from the tailings. Control technologies typically include the application of a cover to reduce the radon release or the provision of an isolation zone around the tailings area to ensure public exposure is minimized.

The technology for radon control is highly advanced. The benefits of covers and the size of the institutional control zone can be determined with air dispersion modelling and radiological pathways analysis. The criteria for radon control are the same as for direct radiation control. The technology for radon control is reviewed in Section 7.4.

4.3.2 PARTICULATE DISPERSION BY WIND

Wind erosion is a common problem at all tailings sites. The primary control technologies are covers that stabilize the surface, and isolation. Covers would commonly include vegetation, waste rock, soil or water. All effectively eliminate wind blown tailings dust.

Wind erosion is normally not a long-term concern as long as the surface is stabilized. Erosion and air dispersion modelling is well established and can define cover requirements. Often, vegetation studies are required to demonstrate that vegetation can be grown on tailings areas.

The objective of wind erosion controls is to ensure that particulate levels and their contained radionuclides are at acceptable levels. The criteria for the control of radiological exposure from wind blown dust are the same as for direct radiation and radon. The technologies for control of wind erosion are discussed in Section 8.2 on erosion control.

Table 4.1-1 Summary of Contaminant Releases, Control Technology, Objectives and Criteria

CONTAMINANT RELEASE/MECHANISMS	CONTROL METHODS	TECHNOLOGY
A) DIRECT RADIATION	i) SHIELDING •EARTH/ROCK COVERS •WATER COVER	i) RADIATION SHIELDING ANALYSIS
	ii) ISOLATION	ii) RADIOLOGICAL PATHWAYS ANALYSIS (DEMOGRAPHY, DOSE CALCULATIONS) •INSTITUTIONAL CONTROL
B) AIR EMISSIONS B(1) RADON RELEASE	i) NATURAL DIFFUSION/RADIOLOGICAL DECAY	i)+ii) RADON DIFFUSION/DECAY MODELLING TO DEFINE COVER DESIGN
	ii) COVERS - EARTHEN, WATER	
	iii) ISOLATION	iii) AIR DISPERSION MODELLING AND RADIOLOGICAL PATHWAY ANALYSIS TO DEFINE DOSE • INSTITUTIONAL CONTROL
B(2) PARTICULATE DISPERSION BY WIND	i) COVERS - VEGETATION, EARTH/ROCK, WATER	i)• AIR DISPERSION MODELLING AND WIND EROSION MODELLING TO DEFINE COVER REQUIREMENTS • REVEGETATION ANALYSIS
	ii) ISOLATION	ii) RADIOLOGICAL PATHWAYS ANALYSIS
C) SURFACE WATER RUNOFF C(1) HYDRAULICS	i) DIVERSION, STORAGE, DECANT TO TREATMENT EMERGENCY RELEASES	i)• FLOOD PREDICTIONS • CHANNEL HYDRAULICS/MAINTENANCE • WATER BALANCE CALCULATIONS • DECANT AND SPILLWAY DESIGN
C(2) DISSOLVED AND SUSPENDED CONTAMINANTS	i) COLLECTION AND TREATMENT	i)• WATER TREATMENT/SLUDGE DISPOSAL •PROHIBIT DIRECT SURFACE WATER RELEASE
	ii) EROSION CONTROL	ii)•COVERS - SOIL/ROCK, VEGETATION, WATER •EROSION MODELLING
	iii) DILUTION	iii) SITING • WATER REUSE/DIVERSION • PATHWAYS ANALYSIS, INSTITUTIONAL CONTROL
D) SUBSURFACE SEEPAGES	i) INFILTRATION BARRIERS	i)• VEGETATION, DRAINS, LINERS, ENGINEERED CAPS, WASTE ROCK, ETC. • INFILTRATION MODELLING
	ii) NATURAL AND MAN-MADE LINERS	ii) SYNTHETIC LINERS, CLAY OR BENTONITE MODIFIED LINERS, LOW PERMEABILITY BASINS, GROUT CURTAINS, TILL CORE CUTOFFS • HYDRAULIC MODELLING
	iii) ATTENUATION BARRIERS	iii) GEOCHEMICAL TRANSPORT MODELLING
	iv) COLLECTION AND TREATMENT	iv) INTERCEPTOR DRAINS, INTERCEPTOR WELLS, DEWATERING WELLS • WATER TREATMENT AND SLUDGE DISPOSAL
	v) ISOLATION	v) PATHWAYS ANALYSIS/INSTITUTIONAL CONTROL
E) ACID GENERATION	i) COVERS - EARTHEN, WATER, LINERS	i) ACID GENERATION MODELLING (RATAP)
	ii) CHEMICAL TREATMENT	ii) PYRITE REMOVAL OR LIMESTONE ADDITION
	iii) COLLECTION AND TREATMENT	iii) WATER TREATMENT AND SLUDGE DISPOSAL
F) MAJOR CONTAINMENT FAILURES	i) DAMS	i) SLOPE STABILITY AND EARTHQUAKE ANALYSIS
	ii) PLACEMENT STRATEGIES	ii)•THICKENED TAILINGS •DEWATERING SYSTEMS
	iii) FROST ACTION CONTROL	iii) THERMAL COVER, VEGETATION, WASTE ROCK •DESIGNS FOR SETTLEMENT OR HEAVE
	iv) SITING	iv) SITE SELECTION • FOUNDATION CONDITIONS • HYDRAULICS
• SUMMARY	• HIGHLY SITE SPECIFIC AND MAY INVOLVE ISOLATION. THIS IS ESPECIALLY TRUE FOR REMOTE NORTHERN SITES.	• HIGHLY SITE AND TAILINGS SPECIFIC. ADVANTAGE IS TAKEN OF THE FLEXIBLE NATURE OF REGULATORY CRITERIA

OBJECTIVES	CRITERIA	
	SHORT-TERM (OPERATIONS)	LONG-TERM (CLOSE-OUT)
i)• REDUCTION OF DIRECT RADIATION LEVELS TO PERMISSABLE LEVELS • IN THE ABSENCE OF INSTITUTIONAL CONTROLS, RISK NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS ii)•RADIOLOGICAL DOSES TO BE LESS THAN PERMISSABLE LEVELS AND ALARA •REDUCE AREA UNDER INSTITUTIONAL CONTROL TO A MINIMUM	•OCCUPATIONAL DOSE EQUIVALENT NOT TO EXCEED 50 mS/YR •PUBLIC DOSE EQUIVALENT NOT TO EXCEED 5 m Sv/yr. •DOSE EQUIVALENTS TO BE ALARA	• UNWRITTEN OBJECTIVE FOR SURFACE GAMMA LEVELS NOT TO EXCEED 2.5 m Sv/h • RISKS NOT TO EXCEED 10 X 10^{-6}/YR SERIOUS HEALTH EFFECTS WITHOUT INSTITUTIONAL CONTROL • WITH INSTITUTIONAL CONTROLS DOSES MUST BE ALARA
i)• REDUCTION OF RADON RELEASES TO ACCEPTABLE LEVELS •IN THE ABSENCE OF INSTITUTIONAL CONTROLS, RISK NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS ii) AS IN (i) ABOVE	AS ABOVE	• NO WRITTEN CRITERIA FOR RADON RELEASE RATES (EPA STANDARD IS 20 pCi/m^2/s ABOVE BACKGROUND) • RISKS NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS WITHOUT INSTITUTIONAL CONTROLS
i) •REDUCTION OF AIRBORNE PARTICULATE TO ACCEPTABLE LEVELS •IN THE ABSENCE OF INSTITUTIONAL CONTROL, RISK NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS ii) AS IN (i) ABOVE	AS ABOVE	• WITH INSTITUTIONAL CONTROLS DOSES MUST BE ALARA TO MINIMIZE THE GEOGRAPHICAL AREA UNDER CONTROLS
i)• MINIMIZE THE AMOUNT OF CONTAMINATED WATER • INTERCEPT AND TREAT AS MUCH WATER AS PRACTICAL • MINIMIZE DOWNSTREAM EFFECTS ON WATER QUALITY • ENSURE ALL STRUCTURES HAVE ADEQUATE HYDRAULIC CAPACITY TO PROHIBIT MAJOR FAILURES • ENSURE THE HEALTH AND SAFETY OF THE PUBLIC	•STORAGE IS NORMALLY PROVIDED TO PERMIT COLLECTION AND TREATMENT OF THE WORST STORM ON RECORD (REGIONAL STORM) •SPILLWAYS ARE DESIGNED TO PASS THE PROBABLE MAXIMUM FLOOD WITH ADEQUATE FREEBOARD ON DAMS/DYKES	•SPILLWAYS ARE DESIGNED TO PASS THE PROBABLE MAXIMUM FLOOD
i)• MEET MINIMUM DISCHARGE OBJECTIVES • MINIMIZE EFFECTS ON DOWNSTREAM WATER QUALITY • MINIMIZE RADIOLOGICAL RELEASES ii)• MINIMIZE SURFACE EROSION AND MAINTAIN A STABLE PILE • MINIMIZE RADIOLOGICAL RELEASES AND DOWNSTREAM WATER QUALITY EFFECTS iii)•MINIMIZE RECEIVING WATERBODY CONCENTRATIONS •MINIMIZE HEALTH EFFECTS	•MINING EFFLUENT DISCHARGE STANDARDS	•SITE SPECIFIC WATER QUALITY DISCHARGE CRITERIA •SURFACE WATER QUALITY OBJECTIVES AND DRINKING WATER STANDARDS •LONG TERM STRUCTURE STABILITY •RISKS NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS WITHOUT INSTITUTIONAL CONTROL •RISKS AND ENVIRONMENTAL EFFECTS TO BE ALARA WITH INSTITUTIONAL CONTROL
i) • TO MINIMIZE SEEPAGE OR CONVERSELY ENCOURAGE SEEPAGE AND PREVENT SURFACE DISCHARGE ii)• TO MINIMIZE SEEPAGE LOSSES FROM THE BASIN THUS MINIMIZE THE EFFECTS ON GROUNDWATER QUALITY iii)•TO RETARD THE MIGRATION RATE OF CONTAMINANTS. WHERE APPROPRIATE PERMIT RADIOACTIVE DECAY TO CONTROL RELEASES TO ACCEPTABLE LEVELS iv)•TO IMPROVE DOWNSTREAM WATER QUALITY v)•MINIMIZE HEALTH EFFECTS	•MINIMIZE ENVIRONMENTAL EFFECTS	•GROUNDWATER QUALITY AND DRINKING WATER QUALITY OBJECTIVES •SURFACE WATER QUALITY OBJECTIVES AT THE POINT OF DISCHARGE •RISKS NOT TO EXCEED 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS WITHOUT INSTITUTIONAL CONTROL •RISKS AND ENVIRONMENTAL EFFECTS TO BE ALARA WITH INSTITUTIONAL CONTROL
i)• MINIMIZE ACID GENERATION RATES THROUGH COVER APPLICATION ii)• MINIMIZE ACID GENERATION RATES BY REDUCING PYRITE CONTENT OR MAINTAINING NEUTRAL CONDITIONS iii)•MEET DISCHARGE OBJECTIVES AND MINIMIZE DOWNSTREAM EFFECTS	•MINING EFFLUENT DISCHARGE STANDARDS	•SITE SPECIFIC WATER QUALITY DISCHARGE CRITERIA •SURFACE WATER QUALITY CRITERIA AND DRINKING WATER OBJECTIVES
i)• PROVIDE ACCEPTABLE STATIC AND DYNAMIC STABILITY • PROVIDE LONG TERM STABILITY • SLOW DEGRADATION VERSUS RAPID CATASTROPHIC FAILURE ii)•IMPROVE PHYSICAL PROPERTIES OF TAILINGS •MAXIMIZE DEPOSIT DENSITY AND MINIMIZE WATER CONTENT WHERE APPROPRIATE •REDUCE LIQUEFACTION POTENTIAL	•GOOD ENGINEERING PRACTICE •STRUCTURES TO HAVE ADEQUATE FACTORS OF SAFETY UNDER CREDIBLE MAXIMUM EARTHQUAKE	•PROVIDE STRUCTURES THAT DEGRADE SLOWLY RATHER THAN FAIL RAPIDLY
iii)•DEVELOP STABLE FROST CONDITIONS •DEVELOP STABLE COVERS RESISTANT TO FROST ACTION iv)•MINIMIZE THE POTENTIAL FOR FAILURE BY SELECTING GOOD FOUNDATIONS AND SITES WITH MINIMUM WATERSHEDS	•MINIMIZE DEGRADEABLE FROST	•STABILIZE FROST CONDITIONS
• PUBLIC HEALTH AND SAFETY • ENVIRONMENTAL PROTECTION	•FEDERAL EFFLUENT DISCHARGE STANDARDS AND PERMISSIBLE RADIOLOGICAL DOSE EQUIVALENTS •PROVINCIAL ENVIRONMENTAL CRITERIA	•SURFACE WATER QUALITY OBJECTIVES •RISK TO BE LESS THAN 1 X 10^{-6}/YR SERIOUS HEALTH EFFECTS IF NO INSTITUTIONAL CONTROLS APPLIED •RISKS AND ENVIRONMENTAL EFFECTS TO BE ALARA WITH INSTITUTIONAL CONTROLS

4.4 SURFACE WATER RUNOFF

4.4.1 HYDRAULICS

Water management practices are a key to the successful operation and close-out of a tailings basin. Water flows are controlled through diversion, storage, decant to treatment or emergency spillways. The design basis of control structures is well advanced and relies on hydrologic modelling from precipitation and climate records.

The objectives of the water management plans are typically to maximize the diversion of clean water from the site, minimize discharge volumes, ensure adequate storage for stormwaters and ensure that structures are hydraulically sized to prevent a major failure such as the overtopping of a dam. Criteria are highly site specific but normally basins are designed to store and treat waters from major storms with spillways to pass the flows associated with a probable maximum flood or other design events.

4.4.2 DISSOLVED AND SUSPENDED CONTAMINANT RELEASES

Contaminant releases and their resultant environmental effects are controlled through the collection and treatment of runoff, erosion control and by dilution. Water treatment techniques are well advanced for all contaminants and are briefly reviewed in Section 7.5. Sludge disposal is a potential problem for some sites and current practices are discussed in Section 7.5. Water erosion is controlled through surface stabilization and in some cases settling ponds within the tailings basins. Erosion control methods and modelling technologies are reviewed in Section 8.2.

In the long-term, dilution is often a key to the minimization of the impact of surface discharges from a reclaimed facility. Contaminant releases cannot be prevented therefore the effects can be minimized at sites where large dilution flows are available.

Over the short-term, mining effluents must meet Federal Discharge Standards. In many cases, additional constraints are placed in the operating licence. Over the long-term, the prime objectives are to meet provincial water quality objectives at a selected downstream receptor. Radiological risks are normally assessed through a radiological pathways analysis and where appropriate, an ALARA analysis is conducted to determine if additional controls on waterborne contaminants are necessary.

4.5 INFILTRATION & SUBSURFACE SEEPAGES

Control methods for reducing seepage rates and their environmental effects include infiltration barriers, basin liners, attenuation barriers and the collection and treatment of seepage. In selected cases isolation zones may also be required in the groundwater plume down gradient of the basin. The technology for the design of these control methods is reviewed in Section 7.3.

Covers which affect infiltration include vegetation, soil, waste rock, and engineered caps with drains and liners. The effectiveness of these covers can be assessed by using infiltration water balance models. Seepage barriers can include synthetic liners, clays, clay modified soils, grout curtains, slurry walls and natural in situ soil and rock. The effectiveness of these barriers is assessed through hydrogeological models. Attenuation barriers normally consist of natural materials in the seepage pathway. Attenuation barriers can also be man-made. These barriers retard the rate of contaminant migration and in selected cases may provide sufficient attenuation so as to permit a major reduction in the plume concentration resulting from radioactive decay. Interceptor drains provide for active collection and treatment of seepage. Pathways analyses and water quality standards can be utilized to size a zone of institutional control over groundwater use.

The objectives of seepage control technologies is to simply minimize the impact on groundwater and surface water receptors. Most provincial agencies have groundwater quality objectives which must be met at a downstream point of control.

4.6 ACID GENERATION

Acid generation and the subsequent release of acid waters can have major environmental effects. Acid pH levels are conducive to the dissolution of many metals and acidity itself can cause major pH depressions in the receiving waters. Control methods for acid generation include covers, flooding, chemical treatment of the tailings and collection and treatment of the runoff.

Covers should be effective in reducing acid generation rates but may not eliminate the acidity problem unless the water table rises into the cover and thus floods the tailings, effectively leading to water cover. Sulphide removal or the addition of a buffering agent such as limestone can also be an effective control. Collection and treatment is a practical, short-term management strategy but may not be a viable long-term control method. The technology for acid generation control is discussed in Section 8.5. Treatment of acid waters and disposal of the sludges are reviewed in Sections 8.5.

4.7 MAJOR CONTAINMENT FAILURES

Containment is provided by natural basins and man-made structures. Control and procedures methods to ensure long-term containment are centered around good siting, tailings placement strategies, frost control (where applicable) and good engineering practices. Site selection aspects are addressed in Section 6.1 and placement strategies are reviewed in Section 6.2. The disruptive effects of frost in permafrost are addressed in Section 8.4. Good engineering practices include dam designs with adequate safety factors, seismic analysis, and careful engineering supervision and control during construction. Hydraulic design is also a key to ensuring dams have adequate freeboard and that spillways are sized to handle the maximum probable flows. The design of control structures, diversion ditches and spillways are reviewed in Sections 7.1 and 7.2.

The objectives of containment technology is to provide dams and tailings beaches that are stable under static and dynamic conditions with adequate long-term durability to prohibit rapid degradation and catastrophic failure. Given that nature will eventually degrade all structures, the containment structure and tailings beaches should deteriorate very slowly to prevent catastrophic releases.

CHAPTER 5.0
TYPICAL CANADIAN URANIUM TAILINGS IMPOUNDMENTS

Four generic Canadian uranium tailings impoundments are described in this chapter to provide the reader with a detailed description of typical conditions and technology. These typical impoundments are essentially the same generic models considered by Steffen Robertson and Kirsten 1986, in their evaluation of appropriate technology for the long-term stabilization of uranium tailings control structures and covers. The main observations of this evaluation are summarized to demonstrate the major factors influencing long-term impoundment stabilization and contaminant control, and the effectiveness of some of the basic control technology.

5.1 SITE CHARACTERISTICS IN GENERAL

Particular sites in Ontario and Saskatchewan have not been chosen, but rather generic models typical of conditions and waste technology at a number of similar sites are described. In Chapter 3 a description was provided of the mining, milling and waste disposal facilities at all of the Canadian uranium production sites.

The Elliot Lake district of Ontario represents much of the older technology which consisted of "depositing the waste rock and tailings in impoundments behind leaky, valley dams in lake, bog or stream valleys", (Snodgrass et al 1982). The newer generation of Elliot Lake impoundments incorporate seepage control measures and designs provide for vegetative covers. Mining and milling in the Elliot Lake district has been going on for more than 30 years and it is estimated that more than 100 million tonnes of tailings have been generated by the thirteen separate mines and eleven mills.

In the other principal uranium mining area in Canada in Northern Saskatchewan major production is more recent and newer waste disposal technology is used. So far about 30 million tonnes of tailings have been generated, but the early material, representing about 30 percent of this amount, was either placed behind non-engineered dams or discharged into lakes or used as mine backfill. Currently three mines are active all having commenced operations in the 1980's.

Both the Ontario and Saskatchewan sites are characterized by ridges separated by lower areas consisting of numerous lakes and swamps. The geology differs in detail, but essentially it is similar, consisting of shallow glacial deposits and recent organics over bedrock. The glacial soils are either till, deficient in clay minerals, or outwash sands and gravels. This is different from the uranium mining districts in the U.S.A., where the overburden soils are thick and clay rich, with the potential for being very active retardants of contaminants in the tailing seepage water as a result of the high ion exchange capacity of the clays. This is yet another reason why a direct transfer of U.S. technology to Canadian situations may be inappropriate.

Furthermore water tables and soil moisture contents are high in Canada, decreasing radon emanation rates. Infiltration is rapid and seepage is generally fast over short distances. The water quality is high with low dissolved solids. In the U.S.A. water tables are often deep and seepage rates slow. In Ontario precipitation usually exceeds evaporation, while there is a deficit in Northern Saskatchewan and particularly so in the American Southwest. This means that zero release systems cannot be adopted at Ontario sites. If runoff and seepage are not of acceptable quality standards for discharge to adjacent surface waters, some form of long-term water treatment is indicated and this is cumbersome if not infeasible. The alternative is to reduce discharge rates to levels where dilution in surrounding groundwater is feasible. On a long-term basis this may be a practicable approach as the French research workers now seem to believe, (Farges et al 1986).

Vegetative cover is comparatively easy to establish in Canada, forests being the climax type at most sites. The growth of vegetation is helped by high precipitation and groundwater tables.

Disruption of earth covers as a result of frost heave is an issue that should be addressed in Canada, but the beneficial effects of permanently frozen ground, where such conditions can be established, may be useful for long-term stabilization of either tailings deposits or impoundment structures.

5.1.1 SPECIFIC SITE CONDITIONS AT ELLIOT LAKE, ONTARIO

The tailings impoundments are situated in glaciated valleys with nearly continuous bedrock rims surrounding the ponds. The bedrock consists of granitic intrusives and metavolcanics overlain unconformably by sedimentary and metasedimentary rocks up to 2000 m thick. In general sedimentary bedrock consists of quartzite, arkose, argillite and siltstone, with minor carbonates and conglomerates. The local ore zone is in pyritized quartz pebble conglomerates near the base of the sedimentary sequence.

A thin veneer of ablation and lodgement till overlies the bedrock. The till is usually a silty sand with gravel and cobbles. Some outwash sands and glacial lacustrine silts and clays overly the tills in lowlying areas. Permeabilities range between 10^{-5} m/s in the outwash deposits to 10^{-7} m/s in the tills, with near surface bedrock permeabilities lying in the same range.

The mining area is beyond the southern margin of the permafrost zone. Mean monthly temperatures range from -12°C in January to +18°C in July, with 183 frost free days per year an average. Mean annual precipitation is 926 mm. The evapotranspiration is 542 mm annually, having a net water surplus of 384 mm, about 100 mm of which is believed to infiltrate into the ground. Drainage is via the Serpent River into the North Channel of Lake Huron.

The natural climax vegetation in the Elliot Lake region is mixed deciduous and coniferous forest, consisting of pines, hemlock, maple, oak and basswood, along with some black spruce and balsam fir. Cattails, rushes and sedges will invade the inactive tailings deposits as do one or two tree species, notably trembling aspen and paper birch. Deer, foxes, gulls, ravens and waterfowl are the predominant fauna.

The land use in the area is broad including recreation and tourism. Tailings sites are within a 20 km radius of the 17,000 peopled town of Elliot Lake, the closest residences to the tailings being about 2 km distant.

5.1.2 SITE CONDITIONS IN NORTHERN SASKATCHEWAN

Uranium mineralization in Saskatchewan lies in regions north of 57° latitude about 600 km north of Saskatoon, the major population centre servicing the industry. The mineralization with the exception of Beaverlodge, Lorado and Gunnar usually occurs at the contact of Athabasca sandstone and older underlying rocks. The sandstone bedrock is covered by glacial till varying in thickness up to about 50 m. The till has been derived from the Athabasca sandstone and it consists mainly of silt and sand. Clay is virtually absent. Topographic depressions are usually infilled with peat. The permeability of the tills average about 1 to 3 x 10^{-6} m/s.

The entire area is within the zone of widespread discontinuous permafrost. The peat filled depressions usually contain ice rich islands of permafrost up to 20 m thick, although it is commonly absent beneath the lakes and numerous shallow pools. Removal of the natural cover of vegetation usually leads to thawing and degradation of the permafrost.

The quality of both surface and groundwater is usually very high with very low mineral content. The regional drainage is mainly from the Athabasca Lake Basin via the Mackenzie River to the Arctic, the remainder flowing east via the Churchill River into Hudson Bay.

The climate type is that of boreal forest with short cool summers. Mean monthly temperatures range from -28 to -25°C in January to +16°C in July. The lakes are generally frozen over from November through to May. The average freezing index for the region is around 3000 degree-days. The mining areas lies between the -1 to -5°C isotherms. Mean annual precipitation is around 400 mm with about two thirds occurring as rain in the summer. Indications are that evaporation exceeds precipitation by around 50 mm annually. Extreme storm events suggest a probable maximum precipitation (PMP) of 300 mm in 24 hrs.

The vegetation is principally coniferous forest of jackpines and black spruce with some birch and balsam fir. Extensive areas have been burned by fires in the past. The lowlands are filled with peat bogs and willow and alder shrubs are common. Large mammals such as moose, caribou, bears, deer and wolves are present along with smaller fur bearing animals and numerous birdlife and migratory waterfowl. Land use is primitive, mainly hunting and fishing by northern residents and tourists.

5.2 SITE 1: ALLUVIAL VALLEY TAILINGS SITE; ELLIOT LAKE

This tailings impoundment is typical of the older tailings impoundments at Elliot Lake.

5.2.1 IMPOUNDMENT LAYOUT AND TAILINGS PROPERTIES

The layout is shown in Fig. 5.2-1. The tailings are approximately 30 m thick and overlie a thin discontinuous blanket of peat over sand and gravel infilling the valley bedrock. About 35 million tonnes of tailings cover 60 ha.

The tailings are fine to medium silty, sands with 10 percent clay. The specific gravity is 2.8. Void ratios range widely from 0.7 to 2.7. The slimes are low to medium plastic. The sand tailings water content is 25 to 30 percent; the fine tailings water content is 50 percent. The underdrained shear strengths of the tailings deposits increase with depth to 4 m after which it remains constant at 15 kPa. Permeabilities are 1×10^{-5} m/s in the coarser tailings and 1×10^{-8} m/s in the slimes.

The ore is low-grade (0.1% U_3O_8) with a high content of pyrite-pyrrhotite (typically 7%).

Oxidation occurs in the upper 3 to 4 m of tailings. When flow is downward, acidic water produced in the unsaturated zone replaces the neutralized tailings water, possibly turning all the tailings water acidic, (Feenstra et al 1981).

5.2.2 PLACEMENT AND TREATMENT OF TAILINGS

The tailings slurry at the mill had a pH of less than 1. It was sequentially neutralized with limestone to a pH of 3.5 and with lime to a pH of 10 to 11. Neutralized tailings were pumped to the impoundment where they were discharged into the north side of the basin. As shown on Figure 5.2-1 there were various discharge points, only one being used at a time. Typically coarse sands settled out on the north side of the impoundment while the slimes deposited in the south. The sands were trafficable at all times after deposition, but the slimes were accessible only when frozen during the winter. Tailings water ponds against the southern arm of the dam at all times during operations, after which, on abandonment, it will be drained and a concrete spillway weir installed.

5.2.3 CONTROL STRUCTURES

The impoundment is closed off by a dyke and embankment dam varying in height up to 20 m. A typical section through the embankment is illustrated as Dam A in Figure 5.2-2. The embankment is constructed of homogeneous waste rock; the material having been crushed to minus 150 mm. It is founded on fluvioglacial sands and gravels that infill the flattish valley to depths of up to 10 m. The embankment material is essentially a rockfill of moderate permeability estimated to be 10^{-3} m/s.

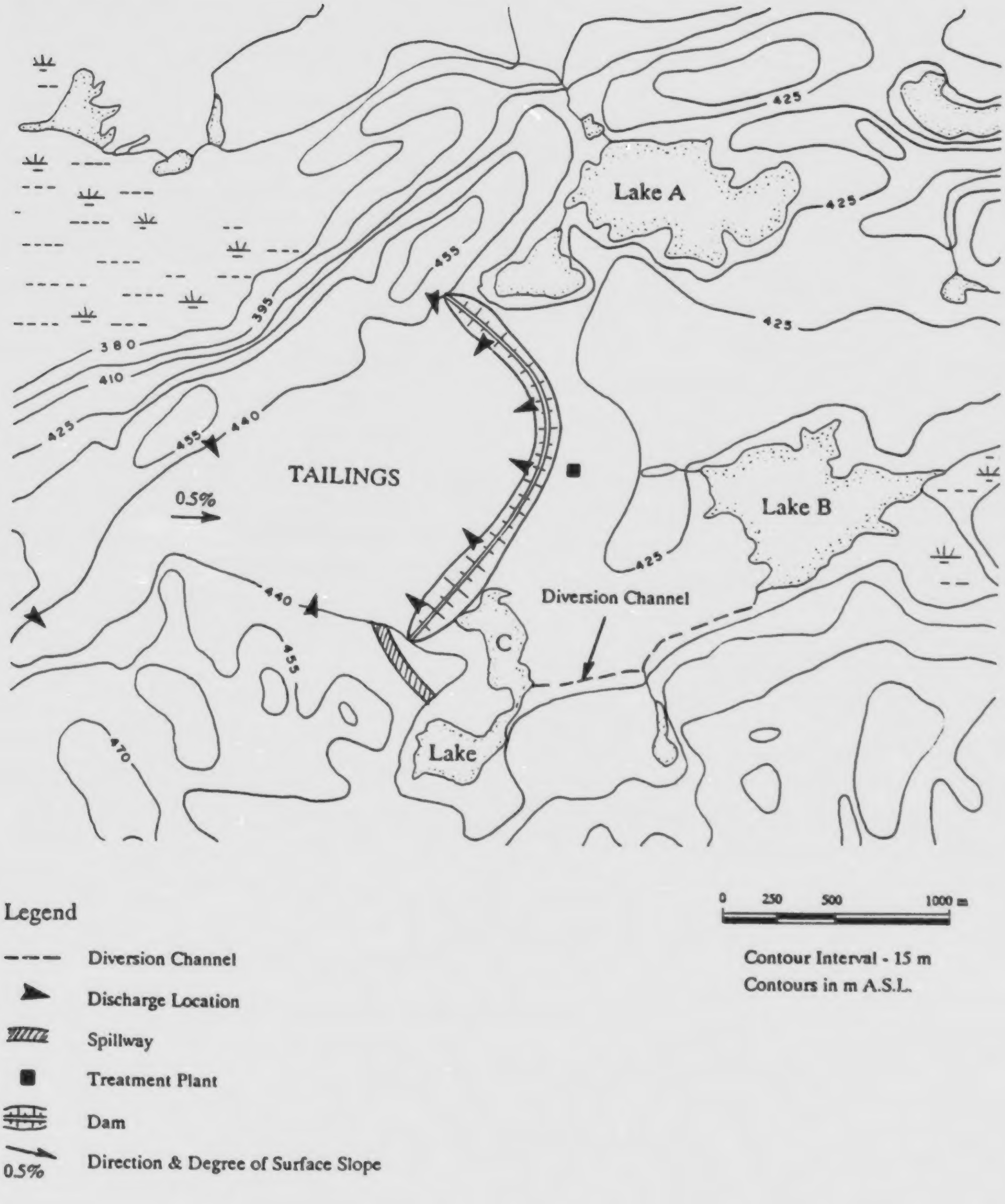
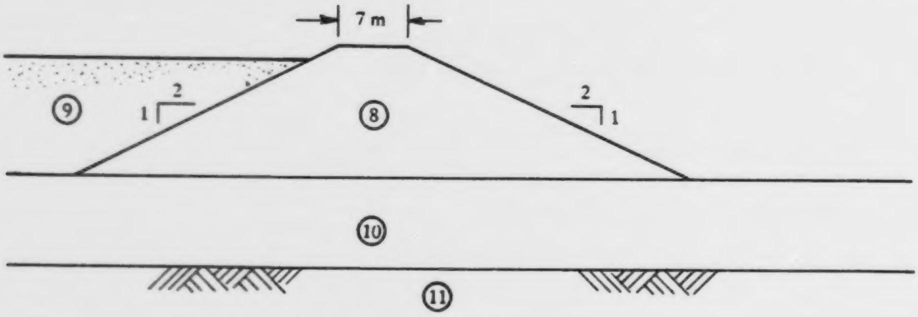
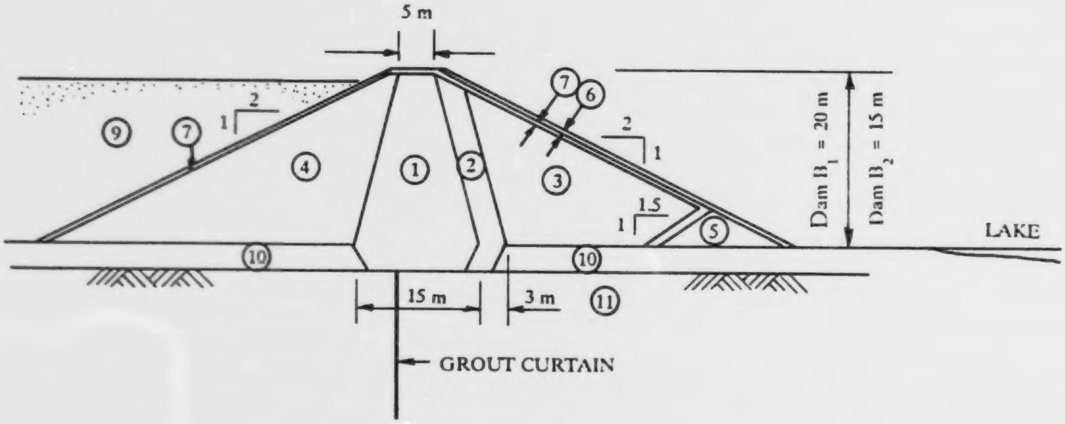

425
425
425
Lake A
455
395
380
410
425
455
440
TAILINGS
0.5%
Lake B
425
Diversion Channel
440
455
C
Lake
470
Legend
Diversion Channel
Discharge Location
Spillway
Treatment Plant
Dam
0.5%
Direction & Degree of Surface Slope
0
250
500
1000 m
Contour Interval - 15 m
Contours in m A.S.L.

Figure 5.2-1 Site Plan - Alluvial Valley Tailings Site (Site 1) - Typical Elliot Lake


7 m
⑨
2
1
⑧
2
1
⑩
⑪

a) DAM A


5 m
⑦
⑥
2
1
⑨
⑦
④
①
②
③
2
1
1.5
1
⑤
Dam B_1 = 20 m
Dam B_2 = 15 m
LAKE
⑩
⑩
15 m
3 m
⑪
GROUT CURTAIN

b) DAMS B_1 AND B_2

LEGEND

① Core and Cutoff Trench - Glacial Till
② Filter - Processed Sand
③ Downstream Shell - Sand and Gravel
④ Upstream Shell - Tailings Sand
⑤ Drain - Processed Gravel
⑥ Erosion Protection - Cobbles
⑦ Bedding/Erosion Protection - Select Sand and Gravel
⑧ Waste Rock
⑨ Tailings
⑩ Overburden/Glaciofluvial Sand and Gravel
⑪ Bedrock

Figure 5.2-2 Typical Cross Sections - Dams A & B Alluvial Valley and Structure Lake Sites

This dam represents structures built at Elliot Lake up to the 1970's after which stricter regulations required well-engineered structures designed to minimize seepage, and constructed to standards and by methods common to water retaining structures.

A 5 m wide spillway channel was provided at the south abutment of the dam and water from Lake C was led in a 500 m long diversion channel to Lake B. The diversion channel was excavated in both overburden and bedrock. The slope of the channel is 0.5%. The section is trapezoidal; the bottom width is 1.8 m; the side slopes are 1V:2H in overburden and IV:0.5H in rock.

Various storms, including the Timmins Storm of 1961, have passed through this generic tailing area. The watershed catchment is 360 ha, 160 ha of which is tailings surface and the remainder forest. The terrain is rocky of moderate relief. Runoff coefficients of 0.7 and 1.0 have been used for forest and tailings to calculate flood routing. A freeboard of 1.5 m was assumed at the dam: this provides 1.2 m for interim storage, and the impoundment was assumed to be empty of water at the time of the storm. Even for the PMP of 424 mm for 12 hours, it was shown that the dam would not be overtopped and in fact the greatest depth of water at the spillway weir would not exceed 0.8 m, which is equivalent to 67% of the available freeboard, at which level the pond would be only 33% full. The peak outflow corresponding to this maximum event was calculated to be 585 m/s, and the water storage would be 1.26 million m^3. The capacity of the pond is large compared to the size of the catchment, 44 percent, accounting for the ease with which such a storm can be handled. The size of the spillway weir was purposely made large to minimize depth of flooding and scour of the vegetated surface of the pond, particularly close the spillway overflow area.

The use of perimeter ditches to divert surface flows around the tailings impoundment, on abandonment was considered. Such ditches would be roughly 7.6 km long. It as concluded that vegetation growth and debris would probably block the ditches in time and thereafter flood water would inevitably drain through the impoundment.

5.2.4 BARRIERS TO SEEPAGE AND EROSION PROTECTION

Since the rockfill embankment is inherently a permeable structure, as are the foundations, no underdrains were incorporated. The dam is situated on 10 m of glacial sands and gravels which have a permeability around 3 x 10^{-5} m/s. The seepage beneath the dam is about 15 L/s. It is treated with lime and barium chloride at the head of Lake C. The quality of water discharging from Lake C meets Ontario Provincial objectives for surface water quality. Since abandonment the quantity of materials required to neutralize the effluent has increased at an accelerating rate.

The advantages and disadvantages of the various cover options are discussed elsewhere (SRK 1986).

Three alternative cover types are reviewed for use prior to abandonment. These include no cover at all, a thin cover and a thick cover. For each of these alternatives there are three material types that are reviewed and details of each approach are summarized in Table 5.2-1.

TABLE 5.2-1
SUMMARY OF ALTERNATIVE COVERS CONSIDERED

A. No Cover

(i) No Action: no reclamation measures would be undertaken to promote revegetation or stabilization of the surface. Once the headpond had been drained, the impoundment would be left to stabilize itself.

(ii) Contour and Direct Vegetation: After the headpond had been drained the tailings surface would be contoured and terraced to an overall slope of about 0.5 % from the north. A revegetation program would be undertaken directly onto this surface.

Construction on the tailings would use wide tracked equipment. Access onto the slimes zones of the impoundment would require improved drainage installed during winter when access is possible. On areas of very poor trafficability which cannot be adequately drained it would be necessary to place sufficient thickness of cover material during winter to allow traffic access in the summer.

(iii) Contour with Pyrite-Free Tailings and Direct Vegetation: a 1 m thick lift of pyrite-free tailings would be hydraulically deposited over the entire impoundment after the headpond had been lowered. This material would then be contoured, terraced and revegetated in a similar manner to the above option. The water table would be held to a depth not exceeding 1 m to reduce pyrite oxidation.

B. Thin Cover (about 0.6 m thickness)

(i) Contour, Soil Cover and Vegetation: After the tailings surface had been contoured and terraced in a similar manner described above, a 0.6 m soil cover composite of locally available silty, sandy till would be placed and the surface revegetated.

(ii) Contour and Waste Rock: a 0.6 m layer of coarse rock would be placed over the top of the contoured tailings surface. The coarse rock would be well graded, competent minus 250 mm material, obtained in part from mine waste rock and from local quarried rock.

(iii) Water: The third approach within the thin cover category is flooding of the tailings impoundment with 0.6 m of water. The tailings would have to be extensively recontoured by dredging and other means to achieve a flat surface. Since the crest of the dam was originally designed to be 1.5 m above the final tailings surface it would be necessary to raise it accordingly by the downstream method to ensure 1.5 m of freeboard. In addition to this, supplementary geotechnical analysis and dam improvement would have to be undertaken to ensure its stability as a water retaining structure. It is recognized that practical limitations are severe. Nevertheless, it was included for generic evaluation purposes.

C. Thick Cover (about 3 m thick)

(i) Homogeneous Cover: a 3 m thick cover of silty sandy till would be placed directly over the entire tailings surface. The surface would be contoured and terraced in a manner to direct surface runoff towards the spillway. The surface of the cover material would be revegetated.

(ii) Layered Cover: due to the lack of low permeability material in the vicinity of the tailings impoundment, a layered cover is proposed. The cover would be consist of 1 m of coarse sand and gravel, overlying 1 m of till, over a 1 m thick layer of finer sand and gravel. The lower 1 m of sand and gravel would be used as bedding material for the till.

(iii) Water Cover: The final option entails flooding the impoundment with 3 m of water. As in the case of the previous thin water cover option, the tailings would have to be recontoured and the dam would have to be raised to allow for a 1.5 m freeboard.

Although soil amendments (fertilizers, neutralizing agents) may vary for each of the alternative cover materials, a basic type of herbaceous seeds mixture would be established on all of the cover materials.

The prime component of the seeds mixture would be a legume, birdsfoot trefoil. Additional components would be one or more of various grass species selected from, for example, creeping red fescue, tall fescue, Kentucky bluegrass, bentgrass and perennial rye grass.

The mixture would be seeded in late May to the end of June. Given average climatic conditions, an herbaceous ground cover of approximately 75% per unit area should be achieved by July/August of the following year. With correct agronomic inputs, such a vegetation cover should be considered permanent and self-sustaining but with time, (>10 years) the type and proportion of species will change as natural plant succession processes occur and indigenous shrub and tree species invade seeded locations. Whether the changing vegetation composition will approach the typical forest types of the Elliot Lake region or will stabilize as a scrub type vegetation seen today is unknown.

No additional erosion protection would be placed on the slopes of the dam, and the coarse waste rock would be relied upon to provide stabilization against rill and gully formation from overland flow off the covered surface of the impoundment.

5.3 SITE 2: STRUCTURE LAKE TAILINGS SITE; ELLIOT LAKE

5.3.1 IMPOUNDMENT LAYOUT AND TAILINGS PROPERTIES

The layout is shown on Figure 5.3-1 and it is similar to Site 1. The basin is almost entirely rock rimmed.

Physically and chemically the tailings also are the same as at Site 1. The ore is the same as Site 1.

5.3.2 PLACEMENT AND TREATMENT OF THE TAILINGS

Similar to Site 1.

5.3.3 CONTROL STRUCTURES

The impoundment is closed off by two dams B_1 and B_2 as shown on Figure 5.3-1. The dams are similar. Bedrock is shallow, and the dams are founded on rock. They are zoned embankments with vertical cores and shallow cutoff trenches of compacted glacial till. To minimize seepage through the rock cement grout curtains are provided at the base of the cutoffs. Additional foundations treatment includes dental concrete, and some shotcrete and slush grouting.

The upstream shells are built of compacted tailings sand, while the downstream shells are compacted pit run sand and gravel very low in radionuclides and classified as environmentally "clean". The glacial till in the core is a well-graded, gravelly, silty sand of low plasticity, and low permeability (10^{-6} to 10^{-9} m/s) when compacted to the standard optimum state. To protect the core from possible seepage

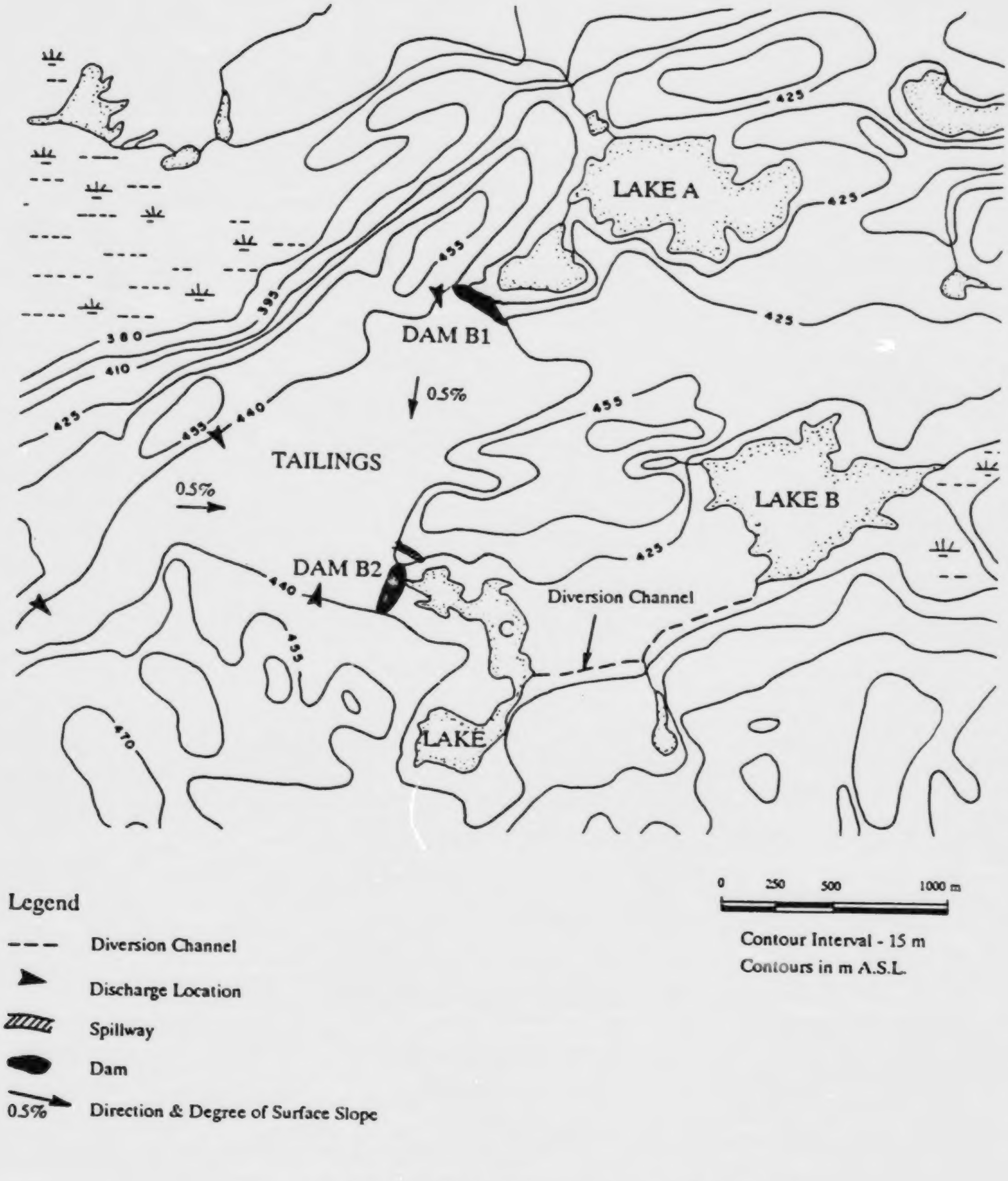

LAKE A
425
425
425
455
395
380
410
425
440
455
DAM B1
0.5%
TAILINGS
0.5%
455
LAKE B
425
DAM B2
440
455
Diversion Channel
C
LAKE
470
Legend
Diversion Channel
Discharge Location
Spillway
Dam
0.5%
Direction & Degree of Surface Slope
0
250
500
1000 m
Contour Interval - 15 m
Contours in m A.S.L.

Figure 5.3-1 Site Plan - Structure Lake Tailings Site (Site 2) - Typical Elliot Lake

erosion, a filter zone of gravelly sand free of fines is placed at the contact of the downstream face with the shell.

At the toe of the downstream shell is a drain of processed gravel protected by a thin filter zone of coarse sand and gravel.

Dams B_1 and B_2 are 300 and 230 m long respectively, and details of the geometry and zones are shown on Figure 5.2-2. Details of the geotechnical properties of the different materials can be found elsewhere (SRK 1986). The dams are typical of structures built at Elliot Lake in the last decade.

Diversion channels and a spillway on Dam B_2 were installed in a similar manner as at Site 1.

5.3.4 BARRIERS TO SEEPAGE AND EROSION PROTECTION

Natural geological materials have been used in place of constructed liners for the base of the impoundment. The dams have low permeability core zones and cutoff trenches taken to bedrock, which is treated by grouting. Based on packer test results the upper 6 m of untreated rock indicated permeabilities ranging from 10^{-5} to 10^{-8} m/s with increasing depth. The grout curtain, extends 20 m into the rock, and is the principal seepage control measure. This appears to have reduced the permeability of the upper part of the rock to 10^{-7} m/s. The grout curtain consisted of a single line of primary holes at 6 m spacing, with secondary and tertiary holes between at 3 m and 1.5 m spacings, where primary grout takes were high. The grout used sulphate-resisting cement, and 4 to 12% by weight of bentonite mixed at water/cement ratios ranging from 3:1 to 5:1. The quantity of seepage estimated at each dam is 0.04 L/s, and as a result no treatment has been deemed necessary to date.

The various cover alternatives on abandonment that were described for Site 1 were also considered for the Structure Lake Impoundment.

The slopes of the upstream and downstream zones of the dams are covered with coarse granular materials (riprap) to protect against erosion. The upstream face protection is needed only during operation, apart from the uppermost 1.5 m of freeboard where water cover alternatives are envisaged. The upstream face is sand and gravel, minus 75 mm material, but the downstream face is cobbles and boulders, 200 mm to 1 m sized material.

5.4 SITE 3: WET TAILINGS SITE; SASKATCHEWAN

5.4.1 IMPOUNDMENT LAYOUT AND TAILINGS PROPERTIES

The ore represents the lower grade Saskatchewan deposits (typically 0.5 to 0.6% U_3O_8) and it has low contents of nickel and arsenic. It is characteristic of the relatively "clean" ore mineral mined at Rabbit or Cluff Lakes.

The impoundment is a valley dam in a rock rimmed depression as shown on Figure 5.4-1. The tailings are up to 20 m thick and the surface area of the pond is 75 ha. The storage capacity is about 9 million tonnes.

The tailings slurry from the mill is approximately 40 percent solids by weight, and the material is fine-grained, principally sandy silt. In-situ water contents range from 90 to 100 percent. The specific gravity of the tailings is 2.8, and in situ void ratios ranged from 2.8 to 3.4. Permeabilities are around 5 to 8 x 10^{-6} m/s.

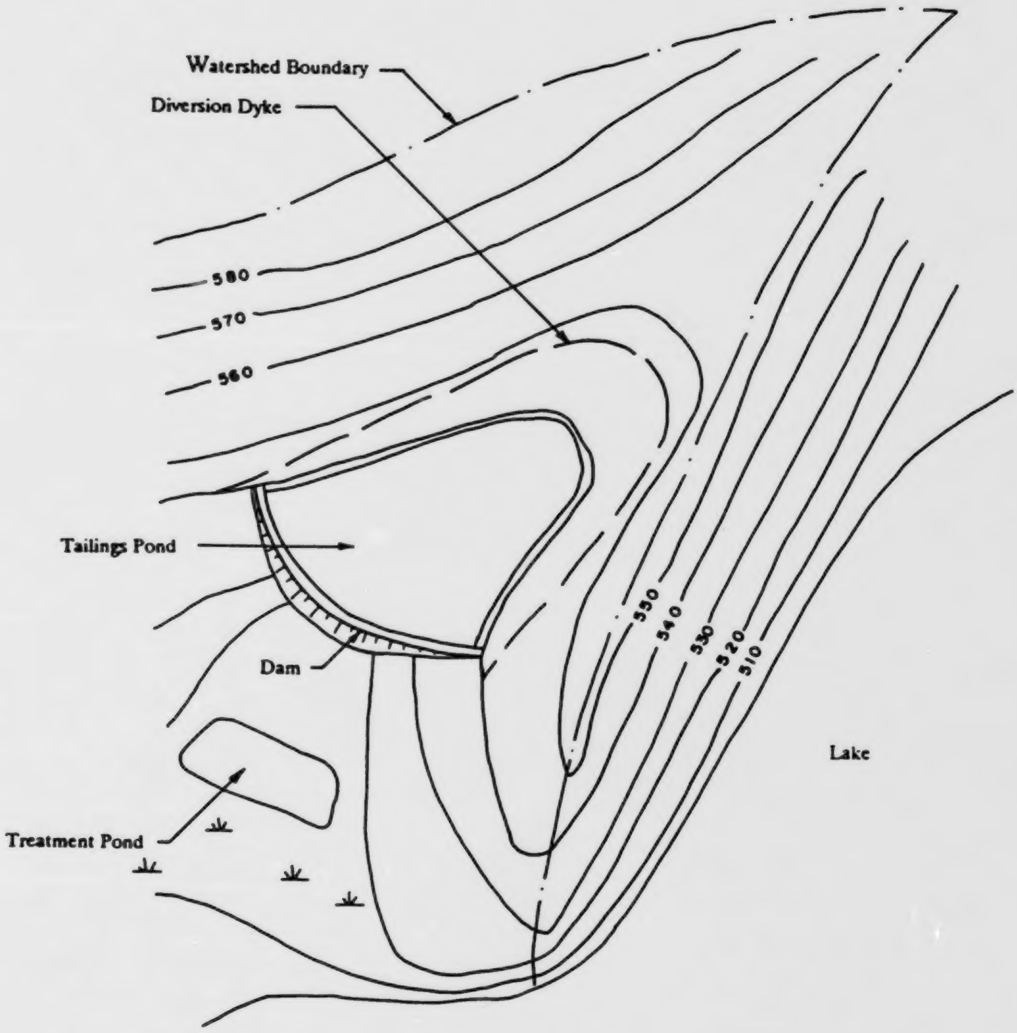

Watershed Boundary
Diversion Dyke
580
570
560
Tailings Pond
Dam
Treatment Pond
550
540
530
520
510
Lake
0
250
500
1000 m

Figure 5.4-1 Site Plan - Wet Tailings Site (Site 3)

5.4.2 PLACEMENT AND TREATMENT OF TAILINGS

Tailings are neutralized and piped from the mill to the tailings pond where they are discharged from along the dam crest to form a central slimes pond. The discharged points are moved periodically to maintain an even distribution and a central decant pond. The coarse tailings are deposited adjacent to the dam, with the slimes settling out in the centre of the basin beneath the decant pond.

Limited areas of the coarse tailings are trafficable in the summer, but most of the surface of the tailings is soft. Access to the frozen tailings is possible in the winter. Discharge points remain fixed during the winter and thicknesses of up to 3 m of frozen tailings accumulate. Frost accumulation measured in the pond at the time of decommissioning is 2 m. The long-term potential for frost aggradation and impoundment surface settlement has a large effect on the stability and performance of any covers placed on the tailings. A rockfill cover would probably maintain the tailings in a permanently frozen state. Studies on the Rabbit Lake impoundment (Geocon 1986) showed that in one area of beach the tailings were frozen over most of their 20 m thickness. Occasional ice lenses 10 to 50 mm thick were found in core samples, together with vertical ice filled fissures 5 to 10 mm thick. They estimated that thawing could lead to surface settlements of between 2 to 5.4 m.

The Geocon studies also brought out the variability in material characteristics in a typical wet tailings impoundment and the influence on consolidation settlements, see Figure 5.4-2. If no thawing of the frozen tailings takes place, the changes in surface gradient, although not negligible, would be small compared to the natural surface slopes of the tailings surface existing prior to decommissioning. They would also tend only to increase the pre-existing surface gradients rather than to reverse them. As a result, no detrimental effects would be expected from these long-term settlements. Design of surface drainage and erosion protection measures would include provisional allowances to accommodate such change in gradients. If, however, complete thawing of the frozen tailings took place, reversal of surface gradients in the transition between the north beach and the clarification pond would take place. Settlements would tend to be irregular due to local variations in quantities of entrained ice and frozen tailings. It would therefore not be possible to accommodate the effects of such an event in design. The possible consequences of large settlements need to be considered.

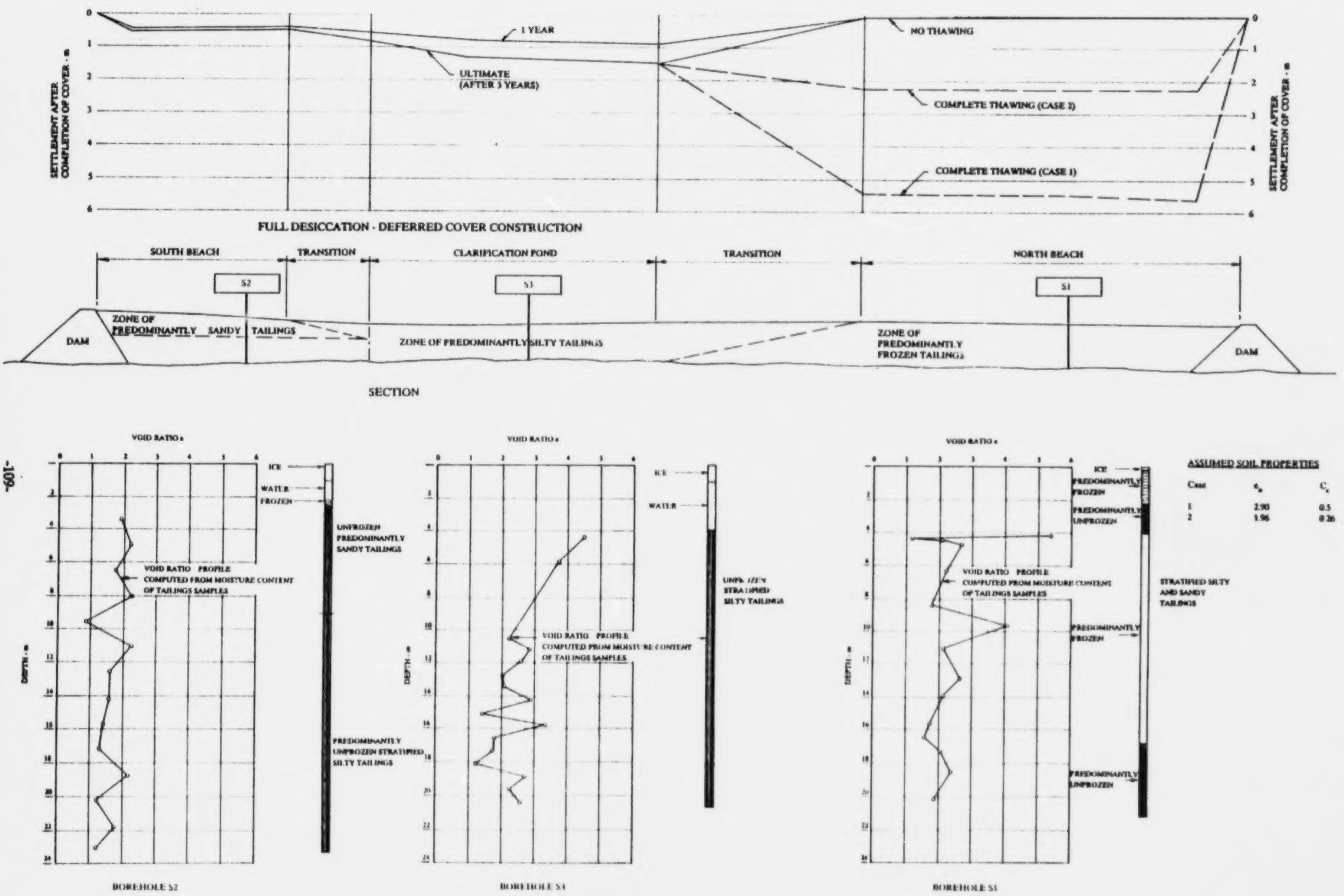
A barge pump is used to decant liquids from the central decant pond, the decant being piped overland to treatment ponds where the supernatant is treated with barium chloride and clarified in a settling pond prior to discharge to the environment. Treatments ponds are constructed of compacted glacial till and lined with a synthetic membrane.

5.4.3 CONTROL STRUCTURES

The major structure is an embankment dam at the southwesterly flank of the impoundment. The dam was constructed in yearly increments using the downstream method. A section through the data is shown on Figure 5.4-3.

Muskeg was stripped from the site and the embankment is founded on undisturbed glacial till. A cutoff was constructed to bedrock. The starter dams, cutoff and the upstream core zone are compacted silty till. The downstream zone is sandy till. Both tills are well graded, low plasticity, and moderately low permeability (1×10^{-6} m/s). A sand filter blanket is beneath the downstream zone and starter dam.

A diversion dyke has been constructed around the uphill flanks of the impoundment and this serves to divert surface runoff discharging it into the lake. No spillway is provided as the pond has adequate storage with a freeboard of 2 m.



ASSUMED SOIL PROPERTIES

Case	e_o	C_c
1	2.90	0.5
2	1.96	0.26

Figure 5.4-2 Variation in Typical Wet Tailings Characteristics and Influence on Settlements (after Geocon 1986)

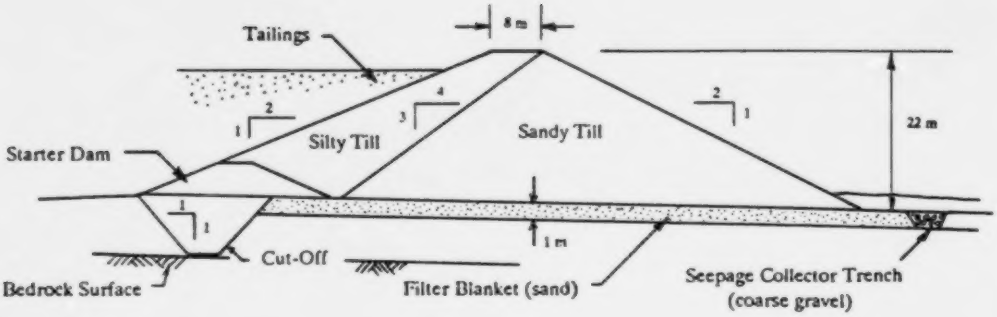


Figure 5.4-3 Dam Cross-Section - Wet Tailings Site (Site 3)

5.4.4 BARRIERS TO SEEPAGE AND EROSION PROTECTION

The impoundment has a seepage collection system consisting of a filter blanket and a gravel filled interception trench to capture seepage water and direct it to treatment facilities at the toe of the containment dam. The filter blanket uses coarse to fine graded clean sand available locally and compacted in 200 mm lifts. The treatment ponds are constructed of compacted till and lined with a synthetic membrane. Liquids from the tailings pond are pumped through a pipeline to the treatment ponds. During operation the supernatant is treated with barium chloride and clarified in a settling pond prior to discharge.

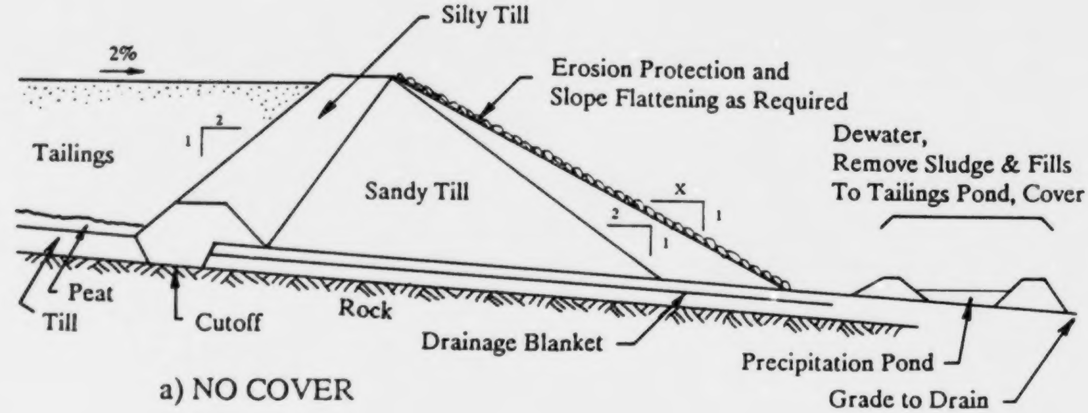
Only natural geological barriers (peat, till and bedrock) line the impoundment. The gneiss bedrock is fractured to 25 m, with an average permeability of 1×10^{-7} m/s. Deeper down the permeability decreases by an order of magnitude to 1×10^{-8} m/sec. Along the flanks of the impoundment the overburden till thins out and is absent in places exposing the rock.

Once the treatment ponds are decommissioned no further seepage control will exist and seepage will discharge freely to the muskeg downstream of the impoundment.

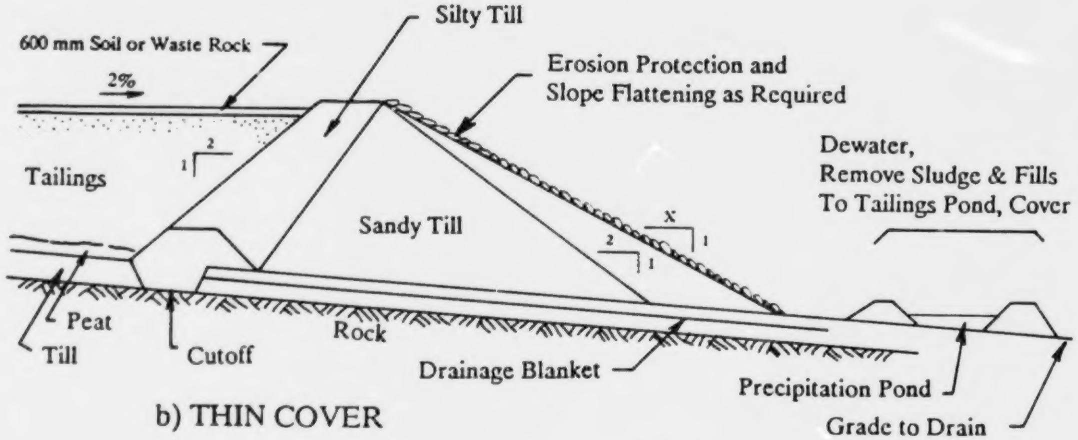
On abandonment, the surface of the tailings is designed to have a 2% cross slope to the lake after consolidation of the tailings. This may take a number of years. On completion of mill operations about 20 m of tailings will have been placed in the impoundment. Based on the results of consolidation tests of samples of the tailings and calculations (SRK 1986), the estimated time for 95% consolidation assuming single drainage is 13 years. Because of the weight of covers further consolidation and settlement up to 2.5 m would occur. Thus some allowance for settlement will need to be made by grading the surface with a camber over and above 2%. Irregularities in tailings deposition and on the development of frozen zones would pose other problems as discussed above.

Cover designs considered include:

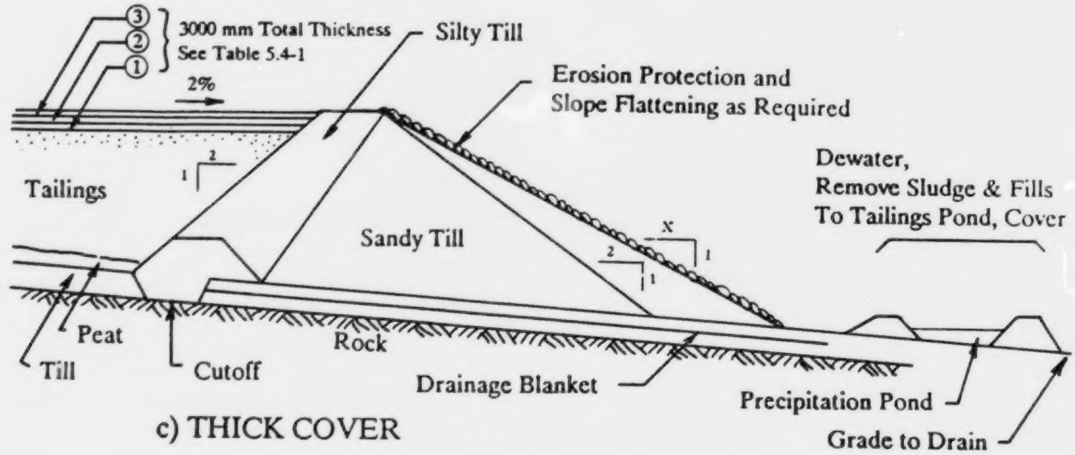
- direct vegetation,
- thin cover (0.6 m) of soil, waste rock with direct vegetation,
- thick cover of common fill and waste rock to some specified thickness depending on the fill type, and


Silty Till
2%
Erosion Protection and
Slope Flattening as Required
Tailings
1
2
Sandy Till
Dewater,
Remove Sludge & Fills
To Tailings Pond, Cover
x
1
2
1
Peat
Till
Cutoff
Rock
Drainage Blanket
Precipitation Pond
Grade to Drain

a) NO COVER


Silty Till
600 mm Soil or Waste Rock
2%
Erosion Protection and
Slope Flattening as Required
Tailings
1
2
Sandy Till
Dewater,
Remove Sludge & Fills
To Tailings Pond, Cover
x
1
2
1
Peat
Till
Cutoff
Rock
Drainage Blanket
Precipitation Pond
Grade to Drain

b) THIN COVER


③
②
①
3000 mm Total Thickness
See Table 5.4-1
Silty Till
2%
Erosion Protection and
Slope Flattening as Required
Tailings
1
2
Sandy Till
Dewater,
Remove Sludge & Fills
To Tailings Pond, Cover
x
1
2
1
Peat
Till
Cutoff
Rock
Drainage Blanket
Precipitation Pond
Grade to Drain

c) THICK COVER

Figure 5.4-4 Decommissioning Cross-Sections - Wet Tailings Site (Site 3)

Note: Vertical Scale Exaggeration

- thick zoned cover (3 m) of soil, waste rock and a soil-bentonite mixture used as a radon barrier.

Typical cross sections through the decommissioned impoundment alternatives are shown on Figure 5.4-4, and details of the design for the thick cover and radon barrier are shown in Table 5.4-1.

The cover will be graded to provide drainage to the perimeter of the impoundment, and to direct surface runoff to the adjacent muskeg and hence into the lake. Flattening the downstream face of the dam to at least IV:3H will be achieved by addition of sandy till placed in horizontal layers and compacted. Where erosion protection is called, for such as on the downstream face of the dam, a layer of crushed rock riprap will be used underlain by a filter blanket of sand and gravel.

The treatment ponds and dykes and the sludges will be removed and deposited within the tailings impoundment shortly after decommissioning.

A diversion dyke will be constructed along the uphill northwest flank of the impoundment to deflect runoff from the watershed around the impoundment.

TABLE 5.4-1
CHARACTERISTICS OF THICK ZONED COVER, W.T. SITE (SRK 1986)

Zone	Thickness (mm)	Purpose	Material Properties
Soil	500	rooting medium	random till borrow
Waste Rock	1500	drainage layer, capillarity break, biobarrier and erosion protection	waste rock, max size 300 mm, 5%-75 um
Soil-bentonite	1000	radon barrier	4% sodium $k=10^{-9}$ m/s

5.5 SITE 4: SEMI-DRY LAYERED TAILINGS SITE; SASKATCHEWAN

5.5.1 IMPOUNDMENT LAYOUT AND TAILINGS PROPERTIES

The impoundment dyke is founded on a blanket of till against a drumlin adjacent to a lake, Figure 5.5-1. The tailings are up to 20 m thick and the surface area of the pond is 90 ha. The storage is about 7 million tonnes.

The tailings are principally soft, compressible sandy silt with an average in situ water content of 132 percent, a specific gravity of 2.64 and void ratios ranging between 4.6 and 5.6. Permeabilities range from 1×10^{-7} to 1×10^{-9} m/s.

The tailings are characteristic of higher grade Saskatchewan ores (typically >2% U_3O_8) and may contain considerable amounts of radiological waste products as well as other toxic elements such as nickel and arsenic, (Knight and Piesold 1985).

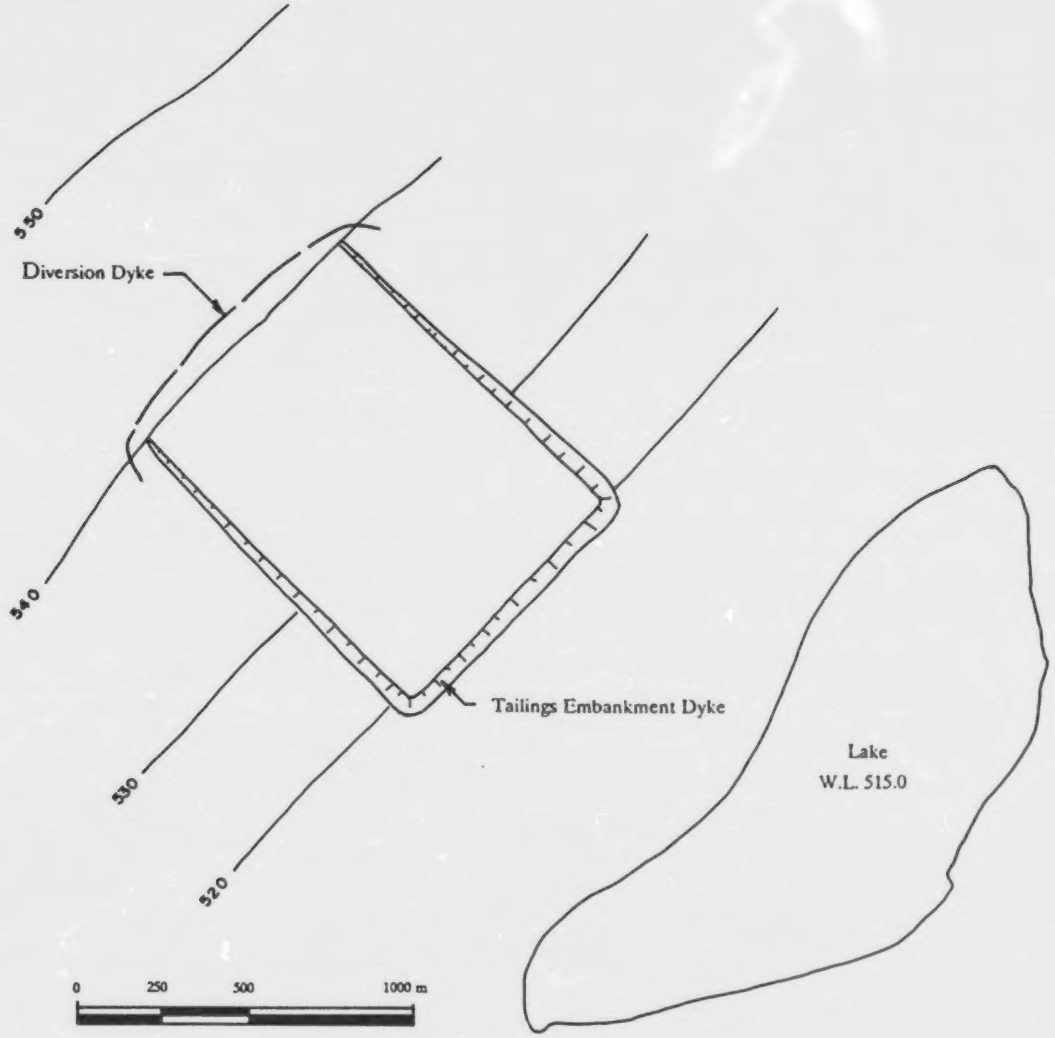

550
Diversion Dyke
540
530
520
Tailings Embankment Dyke
Lake
W.L. 515.0
0
250
500
1000 m

Figure 5.5-1 Site Plan - Semi-Dry Layered Tailings Site (Site 4)

5.5.2 PLACEMENT AND TREATMENT OF TAILINGS

Leached tailings are neutralized with lime to pH 11 or greater and thickened before being pumped by pipeline for discharge to the impoundment.

The tailings slurry is deposited in thin layers over a filter blanket on the impoundment underdrainage systems in a rotational sequence. This produces a tailing beach sloping towards the main embankment, enhances separation of liquids from solids, and yields a laminated tailings deposit with a low vertical permeability. Water ponding against the embankment, drains into the permeable embankment down to the underdrains. Continuous drainage results in a very small pond. Because the tailings surface does not pond water, evaporation is encouraged and this enhances consolidation of the tailings. Tailings have been discharged from the embankment. The method of deposition, known as the sub-aerial method, results in little segregation of materials.

Liquid effluents collected from the underdrainage at the tailings site are pumped to ponds, where they are treated with barium chloride and lime before being clarified and adjusted for pH. They are discharged to the environment.

5.5.3 CONTROL STRUCTURES

The impoundment is on gently sloping ground, and the area within the embankment was initially excavated to a flatter grade sloping in the same direction to accommodate the underdrainage system. The excavated silty, sandy till was used as borrow material to build the dykes. The dyke cross-section is shown in Figure 5.5-2. It contains a sloping core of till modified with bentonite to reduce its permeability. The upstream zone was permeable compacted sand. This serves to decant supernatant liquid and precipitation from the tailing area to the underdrain. Its average permeability was 8×10^{-5} m/s. The upstream face was protected from erosion during operation by a blanket of sandy gravel. The downstream zone is low-plasticity, gravelly, sandy till. The dyke materials were well compacted in 300 mm lifts with a minimum of 4 passes of a vibratory roller.

A dyke was constructed around the impoundment to divert surface runoff to the lake to the southeast. There is no spillway as adequate storage is provided within the impoundment for precipitation that falls directly onto its surface.

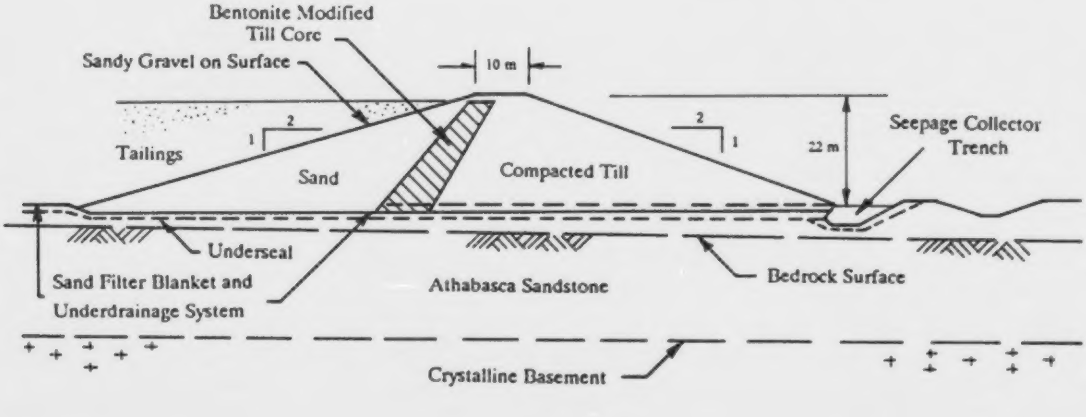


Figure 5.5-2 Main Embankment Cross-Section Semi-Dry Layered Tailings Site (Site 4)

5.5.4 BARRIERS TO SEEPAGE AND EROSION PROTECTION

The impoundment has a seepage collection system consisting of a filter blanket over a compacted, bentonite-modified soil underseal. Seepage enters a sump at the downstream toe of the southeast arm of the dyke.

The liner system is a compacted, bentonite-modified till underseal. The base of the tailings impoundment is graded at approximately 1% downstream to ensure drainage of seepage and supernatant. Typical physical properties of the bentonite-modified liner are shown on Table 5.5-1. Construction of the underseal involved replacing the in situ material with 300 mm of screened till. Bentonite was blended into the till at a rate of between 10 and 18 kg/m^2 at a moulding moisture content of 8 to 11% . The amount of bentonite added varied to achieve the design permeability of 1 x 10^{-8} m/s.

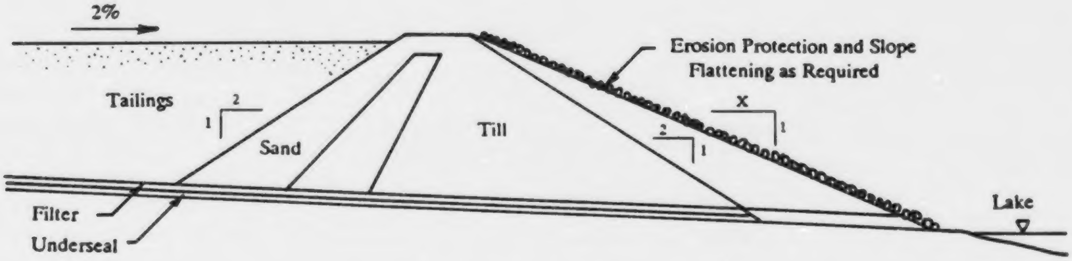
TABLE 5.5-1
PHYSICAL PROPERTIES OF BENTONITE-MODIFIED TILL, SEMI-DRY SITE

Gradation (% by weight)	Gravel	13-26
	Sand	59-74
	Silt and Clay	13-15
Specific Gravity		2.59
In Situ Water Content (%)		8-11
Atterberg Limits (%)	Liquid Limit	N/A
	Plasticity Index	0-28
Compaction Characteristics	Water Content (%)	6.5
(Modified Proctor Optimum)	Dry Unit Weight (Mg/m^3)	2.15
Permeability (m/s)		1 x 10^{-8}

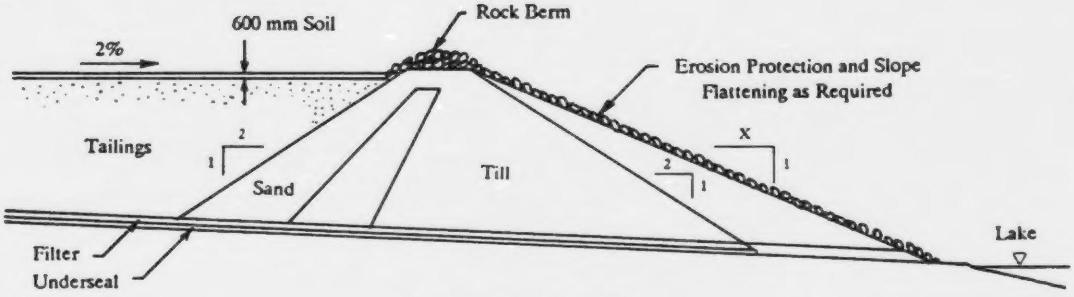
Decommissioning will consist of contouring the tailings to a 2% slope away from the dam after the tailings have consolidated. The tailings could then be covered with:

- direct vegetation, or,
- thin (0.6 m) till, or,
- thick (3 m) cover of common fill (sand and/or till), or,
- thick (3 m) zoned covers for maximum radon attenuation

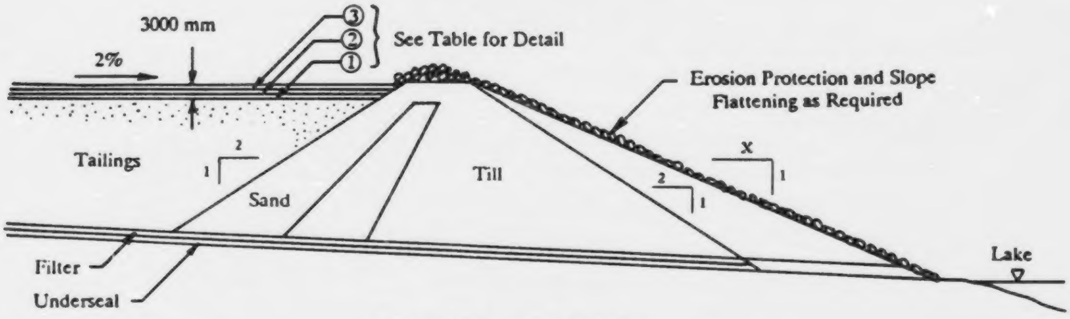
In all cases the sand filter could be extended and the dyke slopes flattened and protected against erosion using riprap. Slopes would be flattened to between IV:3H and IV:6H. The dykes would divert drainage around the deposit. A typical layout and sections for the scheme is shown in Figure 5.5-3. Table 5.5-2 summarizes the characteristics of the thick zoned cover.


2%
Tailings
1
2
Sand
Till
Erosion Protection and Slope Flattening as Required
x
1
2
1
Filter
Underseal
Lake

a) NO COVER


600 mm Soil
Rock Berm
2%
Erosion Protection and Slope Flattening as Required
Tailings
1
2
Sand
Till
x
1
2
1
Filter
Underseal
Lake

b) THIN COVER


3000 mm
③
②
①
See Table for Detail
2%
Erosion Protection and Slope Flattening as Required
Tailings
1
2
Sand
Till
x
1
2
1
Filter
Underseal
Lake

c) THICK COVER

Note: Vertical Scale Exaggeration

Figure 5.5-3 Decommissioning Cross-Sections - Semi-Dry Layered Tailings Site (Site 4)

TABLE 5.5-2
CHARACTERISTICS OF THICK ZONED COVER, SEMI-DRY SITE

Zone	Thickness (mm)	Purpose	Materials Properties
Till	500	rooting medium	random till
Sand	1500	drainage, capillarity break	outwash sand, $<5\%$ - 75 um
Soil-bentonite	1000	radon barrier	4% bentonite, $k=10^{-9}$ m/s

Approximately 2.5 m of frost penetration through the cover material and into the tailings was estimated for the freezing index for the area, and a cover consisting of silty till compacted with a dry density of 1.9 Mg/m^3 at an average water content of 8 percent.

At the time of decommissioning, approximately 20 m of tailings will be contained in the impoundment. Estimated consolidation of the tailings due to 600 mm and 3000 mm of cover is 2.4 and 3.0 m. The estimated times for 50% and 95% consolidation for single drainage are 5.3 years and 30.0 years, respectively.

5.6 EVALUATION OF COVER AND STRUCTURAL STABILITY OF GENERIC IMPOUNDMENTS

5.6.1 GENERAL CONCLUSIONS

SRK (1986) evaluated technology for cover design and structural stability of particular Canadian uranium tailings impoundments as well as the generic models of the Ontario and Saskatchewan sites. A number of general conclusions were drawn. It was believed likely that instability at tailings impoundments will result as a combination of factors. Possible scenarios may be:

- debris blockage of a riprap protected drainage channel (spillway) causes flooding resulting in gully erosion adjacent to the channel, causing the channel to be undermined and the riprap to fail. Additional erosion of the now unprotected channel results in deep gully erosion of the embankment and tailings.

- severe freezing causes temporary blockage of the outlet drains from the toe drain of an embankment. This results in high seepage gradients which produce piping failures (seepage erosion) and minor slumping of the toe of the embankment. Slumping destroys the toe drainage system causing permanent blocking of the underdrainage system. A sequence of piping and embankment slumps follows as a result of the high pore pressures in the toe of the embankment. The progressive failure then spreads both along the embankment and back into the impoundment.

- following a severe drought, a forest fire results in the temporary loss of vegetative cover on a successfully revegetated sulphide tailings impoundment. A period of high winds follows, resulting in significant wind erosion on one area of the impoundment before the vegetation recovers. Upward migration of salt occurs in this bare area where previously the effect of vegetation (and hence infiltration) prevented such migration. The salt migration and wind erosion combined, effectively inhibit regeneration of the vegetation. Continued wind erosion results in the release of tailings.

There are many combinations of events that can be postulated, which may result in instability. Within the limits of this study it has been possible to evaluate only some of the contributors to such failures. Furthermore, the differences between stable and unstable conditions are often unclear and speculative. Examples of such uncertainties are:

- Whether aggrading or degrading frost conditions will exist in northern Saskatchewan in a tailings impoundment with particular tailings and cover properties. The result has a large effect on cover stability.

- Rates and effects of salt precipitation (in underdrains) from a salt saturated tailings solution subject to changing chemical environments resulting from oxidation in the partially saturated underdrains.

- The viability of vegetation in the long-term on sulphide tailings with thin soil and the potential for upward salt migration.

In many instances the current state of knowledge is either insufficient, or the technology or the data is insufficiently precise to permit long-term evaluations with accuracy. Such evaluations are no more than speculation. In the interest of providing some measure of the long-term stability of tailings impoundments, and identifying the areas of concern, the evaluations have been extended well into the zone of speculation. Improvements in the state of knowledge and technology will undoubtedly improve the accuracy of evaluation and prediction.

5.6.2 SPECIFIC EVALUATIONS

The stability of the various generic impoundments are summarized in Table 5.6-1. The long-term stability assumes abandonment of the existing impoundment with some form of minimal but appropriate cover in place. The evaluations of future stability are purely subjective evaluations based largely on projections of present conditions and comparisons with natural land forms. The assessment of present conditions and future potential for minor, moderate or severe instability refers purely to the particular mode of instability, and it does not imply any assessment of tailings or contaminant release rates. Releases are prevented at present by both secondary containment measures and by maintenance. Future releases could be prevented by maintenance or by the implementation of alternative reclamation measures.

From this summary it is apparent that the main concerns regarding long-term stability associated with each impoundment are as follows:

5.6.2.1 Alluvial Valley Tailings Site; Elliot Lake - Site 1

This embankment is stable against most of the long-term disruptive forces.

Despite the fact that the embankment is constructed of rock waste it was assessed as having a moderate potential for gully erosion. This result was obtained because of the relatively small and uniform size of the rock waste.

Seepage erosion is considered to be a severe cause of instability due to the potential for the long-term piping of tailings through the rock waste.

A moderate risk of physical instability is assessed for this embankment as a result of the anticipated high phreatic surface and the potential for seepage erosion.

The spillway is located adjacent to the dam. This is considered to be the most vulnerable control structure with a severe potential of failure due to each of the possible failure mechanisms.

TABLE 5.6-1
SUMMARY EVALUATION OF POTENTIAL INSTABILITY OF CONTROL STRUCTURES

	EMBANKMENTS								DIVERSION WORKS				SURFACE WATER QUALITY		
IMPOUNDMENT	Sheet Erosion	Gully Erosion	Flood Erosion	Wind Erosion	Drains Plugging	Frost Action	Seepage Erosion	Physical Instability	Floods	Gully Erosion	Ice & Debris Blockage	Sediment Blockage	Without Treatment	With Treatment	Seepage
A. ONTARIO SITES															
(i) Alluvial Valley	m	M	m	m	m	m	S	M	S	S	S	S	S	m	S
(ii) Structure Lake	m	m	m	m	M	m	m	m	S	S	S	S	m	m	S
B. SASKATCHEWAN SITES															
(i) Wet Tailings Site	m	S	m	M	M	M	m	M	S	S	S	S	M	m	M
(ii) Semi-Dry Tailings Site	m	S	m	M	S	M	S	S	S	S	S	S	S	m	S

NOTES:

(i) IV:2H side slopes

(ii) Forest cover on all embankments except Dams B_1 and B_2 which has heavy riprap covers.

(iii) Thin soil and forest cover on impoundment surfaces (SRK 1986)

(iv)
n - none
m - minor
M - moderate
S - severe

With the relatively high infiltration estimated for the cover, near surface leaching of the tailings will occur. Some of the leachates will be perched on slimes zones and will migrate towards the old pond area near to the south abutment of the dam and be discharged to the surface. Surface waters are expected to become contaminated by this mechanism. It is concluded that, unless water treatment is maintained, this represents a failure or release mechanism of severe concern.

If acid generation continues in the tailings then seepage will represent a severe instability or release mechanism in the long-term.

5.6.2.2 Structure Lake Site; Elliot Lake - Site 2

The embankments to these dams are considered it be relatively stable in the long-term. Of moderate concern is the potential that, if a solution to acid generation in the tailings cannot be found, then acid seepage may result in iron salt precipitation and blockage of the underdrainage systems.

Drainage of the impoundment is towards Dam B_2 and there are no diversion works associated with Dam B_1.

With no surface water discharge and a low seepage from these embankments, the water quality of surface runoff is only of minor concern. If acid generation continues in the tailings then seepage will represent a severe instability or release mechanism in the long-term. The long-term stability of the grout curtain subjected to acidic seepage waters is questionable. However, if acid generation is prevented the grout curtain ought to be stable.

5.6.2.3 Wet Tailings Site; Saskatchewan - Site 3

The potential for instability of this impoundment in the long-term is moderate.

With 2:1 side slopes, there is a severe potential for deep gully erosion. There is a moderate potential for drain plugging, due mainly to solifluction, root action and frost. Frost action is expected to induce seasonal solifluction on the downstream slope. With the potential for gully erosion and increased pore pressures due to drain blockage it is considered that moderate potential for physical instability exists.

A severe potential exists for instability of the long diversion ditch, due to each of the failure mechanisms.

Seepage water quality is expected to be poor during the long-term. Because of the low acid generating potential of these tailings and the relatively low seepage rate, this mechanism has been assessed a moderate level of potential instability or release.

5.6.2.4 Semi-Dry Layered Tailings Site; Saskatchewan - Site 4

The potential for instability of this impoundment is severe.

The high erosion susceptibility of the embankment materials make it likely that severe gully erosion will occur. During periods of temporary loss of vegetative cover (due to forest fires), relatively rapid rates of wind erosion may occur. There appears to be a severe potential of drain blockage due to chemical precipitation, covering of the outlets, root action and frost action. With blockage of the underdrainage system a severe potential exists for seepage erosion of the underseal and embankment.

While only minor diversion works are required it is considered that severe potential exists for the failure of these diversion structures due to each of the mechanisms for failure.

Because of the low permeability of the tailings relative to the cover materials, it is anticipated that contaminated surface water discharges will occur. Unless infiltration is inhibited by an infiltration barrier in the cap or unless long-term treatment is provided, this represents a potentially severe instability.

Long-term seepage of poor quality water is anticipated and this is assessed as a potentially severe mechanism of long-term instability or releases.

Cover stability was evaluated (SRK 1986) and the results are summarized in Table 5.6-2.

TABLE 5.6-2
SUMMARY EVALUATION OF POTENTIAL INSTABILITY OF COVERS

		MODE OF INSTABILITY							
COVER TYPE		Sheet Erosion	Gully Erosion	Wind Erosion	Salt Migration	Differential Settlement	Infiltration	Frost Heave	Radon Emanation
A. ONTARIO SITES									
no cover action	-	S	S	S	M	m	S	m	S
contour and revegetate	-	m-M	S	M	m-M	m	M	m	M
1 m pyrite-free tailings and vegetation	-	m-M	S	m-M	m-M	m	M	m	m
0.6 m soil cover	-	m-M	S	m-M	m-M	m	M	m	m
0.6 m rock cover	-	m	M	m	M	m	S	m	m
0.6 m water cover	-	n	n	M-S	n	m	S	m	m
3 m soil cover	-	m	M	m	m	m	M	m	m
3 m zoned cover	-	m	M	m	m	M	M	m	m
3 m water cover	-	n	n	n	n	m	S	n	m
B. SASKATCHEWAN WET SITE									
no cover action	-	S	S	S	m	m	S	S	S
contour and revegetate	-	m	S	m	m	m	M	M	M
0.6 m soil cover	-	m	S	m	m	m	M	M	m
0.6 m rock cover	-	m	M	m	m	m	S	M	M
3 m soil cover	-	m	M	m	m	m	M	m	m
3 m zoned cover	-	m	m	m	m	M	M	m	m
C. SASKATCHEWAN SEMI-DRY SITE									
no cover action	-	S	S	S	S	m	M	S	S
contour and revegetate	-	S	S	S	S	m	M	S	S
0.6 m soil cover	-	M	S	M	M	m	M	S	M
0.6 m rock cover	-	m	M	m	S	m	M	S	S
3 m soil cover	-	m	M	m	m	m	M	m	M
3 m zoned cover	-	m	M	m	m	M	M	m	m

Key

1. Potential Instability Code

n = none
m = minor

S = severe
M = Moderate

CHAPTER 6.0
SELECTION OF SITES AND DEPOSITION OF TAILINGS

The following three chapters present a review and evaluation of the technology appropriate to the secure containment of uranium tailings, both in the short and long-term. Chapter 6 considers site selection, characterization and evaluation methodology together with the methods for existing deposit characterization and control of deposit characteristics by alternative construction techniques. Chapter 7 addresses those elements of the containment facility which are under the direct design control of the engineer, namely embankments, diversion ditches, liners, covers and interception and treatment facilities. Finally Chapter 8 considers the control technology required or available to counteract the most severe long-term disruptive forces; frost action, erosion and acid generation.

Table 6.1-1 provides a matrix relating the various contaminant release mechanisms to the natural and engineered controls. This matrix serves to illustrate, for example, that liners may be used as a primary control for seepage and a contributary control for acid generation. Seepage can also be controlled by other primary control methods such as site selection, embankments, covers and by the same techniques used for acid generation control.

6.1 SITE SELECTION

6.1.1 BASIC METHODOLOGY

Selecting a uranium tailings impoundment site is the first task in establishing an acceptable disposal facility, which will contain wastes not only in the short-term but also in the very long-term.

The importance of careful, considered site selection cannot be over-emphasized. No amount of elaborate engineering or treatment techniques can overcome the problems resulting from poor site selection, and sometimes the only remedy may be costly relocation of tailings to another disposal site, or continuous monitoring and rehabilitation.

The criteria to be used for selection of the optimum surface site, both with respect to the operational phase of disposal and the performance of the facility on abandonment, are as follows:

- the site must be geologically stable and free from active faults, unstable slopes, caverns, karstic formations, sinkholes or other voids, and the foundation properties, particularly soil overburden, must be capable of adequately supporting the tailings impoundment without significant settlement taking place. Permafrost in overburden is an important consideration in most regions in Northern Canada,
- the geological formations beneath the site must be chemically stable, i.e., they must not react unfavourably with tailings liquids or seepage,
- the geological formations beneath the site should have the minimum permeability consistent with the region and the requirements of seepage control, and
- the site must not be subject to flooding either from below or above the impoundment, and the catchment area (watershed) above the site should be minimized. This criteria does not apply impoundments which are designed to be continuously flooded (underwater).

Site selection must take into consideration the nature and location of construction materials, mill site location, tailings placement methods, discharge objectives and impoundment types and designs discussed in later sections, together with abandonment requirements and long-term stabilization.

TABLE 6.1-1
MATRIX RELATING CONTAMINANT RELEASE MECHANISMS TO CONTROL TECHNOLOGY

X Primary controls
O Contributoary controls
– Little influence

			CONTAMINANT RELEASE MECHANISMS							
			A. Direct Radiation	B. Air Emissions (i) Radon	B. Air Emissions (ii) Particulate	C. Surface Water (i) Hydraulic Failure	C. Surface Water (ii) Dissolved & Susp. Solids	D. Seepage	E. Acid Generation	F. Structural Instability
Natural Controls Release Determined by		Deposit Properties	X	X	O	–	X	X	X	O
		Site Properties	–	–	O	X	O	X	O	X
Engineered Controls	Chapter									
	6	Site selection, characterization and evaluation	–	–	O	X	O	X	O	X
		Deposit development, characteristics and evaluation (placement methods & dewatering)	–	–	–	–	O	X	X	X
	7	Embankments	–	–	X	O	O	X	X	X
		Diversion ditches	–	–	–	X	X	O	–	X
		Liners*	–	–	–	–	–	X	O	–
		Covers*	X	X	X	–	X	X	X	X
		Interception & Treatment & Other Wastes*	X	O	O	O	X	X	X	–
	8	Frost Action Controls	X	X	X	X	X	O	O	X
		Erosion Controls	X	O	X	X	X	–	O	X
		Acid Generation Control*	–	–	–	–	X	X	X	–

*This manual provides detailed description of technology that is peculiar to uranium impoundments. Detailed technology, for dams, diversion ditches, etc., which apply to any form of tailings disposal are fully described in Chapter 9 - Waste Embankment of the CANMET Pit Slope Manual, 1977.

Most site assessment methodologies now involve some quantitative rating of the various factors to aid the designer in making an objective choice. Modern concepts of risk (probability of occurrence multiplied by the severity, or cost of consequences) are incorporated, (IAEA 1981).

Because of the long-term performance requirements considerable thought has to be given to the interaction of the tailings with the specific site that is hosting the facility. While the confinement of solids may be adequate, changes in the tailings composition and the impact of seepage water quality may not be so. A particular concern at some uranium tailings sites in Canada is acid generation. Where this is clearly a potential problem, it is a considerable advantage if the tailings can be disposed of in a rock rimmed basin where they can be permanently flooded. This leads logically to consideration of permanent disposal underwater such as in a natural lake; innumerable candidate sites are available in the principal Canadian uranium districts.

The Canadian site selection process must take account of cold conditions characteristic of the regions. The cold can lead to problems with frost heave, but its influence on site selection is most likely to be as a result of the presence of permafrost in the ground or the potential for the growth of frozen ground within tailings as a possible permanent technique for isolation and stabilization. In this respect the topography and aspect of the site are important. In general in the discontinuous permafrost belt the lakes are not underlain by permafrost.

One of the major restrictions of uranium tailings disposal is that, in contrast to the disposal of fuel or chemical wastes, the volumes are large and it is too costly to transport the material appreciable distances. Hence site selection is automatically restricted to a small zone within close proximity of the mill and mine. The natural corollary to this is that below grade disposal in worked out mines is a logical alternative to surface disposal if operations allow sufficient flexibility to choose. In the real world a clear cut alternative may not be feasible, and a combination of two or three techniques and sites may have to be evaluated in detail before making the final selection.

Finally the alternative of marine disposal applying the French concept of dilution and dispersion should not be ruled out for possible future sites in coastal regions.

The choice of site therefore resolves into above grade or below grade disposal, with below grade being either underground or underwater. In particular most below grade disposal will be saturated, subaqueous either with or without soil or rock inclusion. Under typical conditions found in Canada, although the potential receptor population may be far away, dominant pathways to be considered are surface runoff and groundwater.

The impoundment site selection process needs to take into account the risk of failure. This should be minimized and, if possible, the facility made fail-safe. In a cold, wet environment a below water, in-lake disposal facility is intrinsically more likely to be resistant to long-term erosion and frost action than one situated above grade.

6.1.2 SITE SELECTION METHODOLOGIES

A systematic, rational and objective selection process is needed (Robertson et al 1980) that can be understood in the review and hearing process, which is now very much a part of the licensing process in many countries. The site selection methodology is specific, depending upon ore types, the country and region involved and the placement methods, e.g., dry disposal with a synthetic liner versus semi-dry disposal with a clay liner. Robertson points out the value in early identification of "fatal flaws", defined as any site characteristic sufficiently unfavourable or severe that, taken singly, it will eliminate the site as a candidate for tailing disposal.

Robertson divides the site selection process in two phases as follows:

Phase 1 - Preliminary Evaluation

Task 1 - Regional screening
Task 2 - Identification of sites
Task 3 - Fatal flaw analysis
Task 4 - Investigation of remaining sites
Task 5 - Qualitative evaluation and ranking
Task 6 - Semi-quantitative evaluation and ranking
Task 7 - Cost analysis
Task 8 - Selection of alternatives for detailed investigation

Phase 2 - Detailed Investigation and Evaluation

Task 1 - Detailed investigation of selected sites
Task 2 - Conceptual designs for the sites
Task 3 - Cost evaluation and pollution/exposure risk evaluation for each site
Task 4 - Ranking of sites and prime site selection
Task 5 - Report preparation and documentation suitable for review process

After the completion of Phase 1, a preliminary evaluation report of the alternative sites can be compiled. At this stage, discussion with the various departments participating in the mine evaluation, as well as regulatory agencies, will lead to a decision on which alternatives to pursue for the detailed investigation.

Tailings impoundments siting in North America and South Africa, involve legal and philosophical questions (Caldwell and Robertson 1983). They review the common utilitarian methods of decision-making familiar to engineers, (Keeney 1980) for siting nuclear power facilities. But they also consider the broader ideological issues, which in the case of uranium impoundment siting loom large in most peoples minds. Engineers always feel on firm ground when they can rationalize and quantify matters; thus probabilistic approaches are often used, (Nelson 1982). But other groups of interests doubt such numerical reduction of problems, and will measure things against intuitive standards of judgement. Both parties make contributions that must be weighed in deciding matters. This is dealt with in some depth by Caldwell and Robertson, and the thesis of their paper is that there are many ways of selecting a site for a new impoundment, but that each approach has to:

- identify possible sites,

- compare alternatives,

- communicate to others the subjective and objective criteria affecting the choice of site, and

- substantiate in a rational way the choice of site.

Site selection methodology that is particularly suited to Canadian conditions recognizes 3 basic options for tailings disposal (Caldwell and Welsh 1982).

- marine and lake disposal,
- mine backfill, and
- surface disposal on land.

The methodology of site selection advocated by them is illustrated for a Canadian West Coast project, and shown in the flow chart on Figure 6.1-1. Once again this involves preliminary evaluation by rating

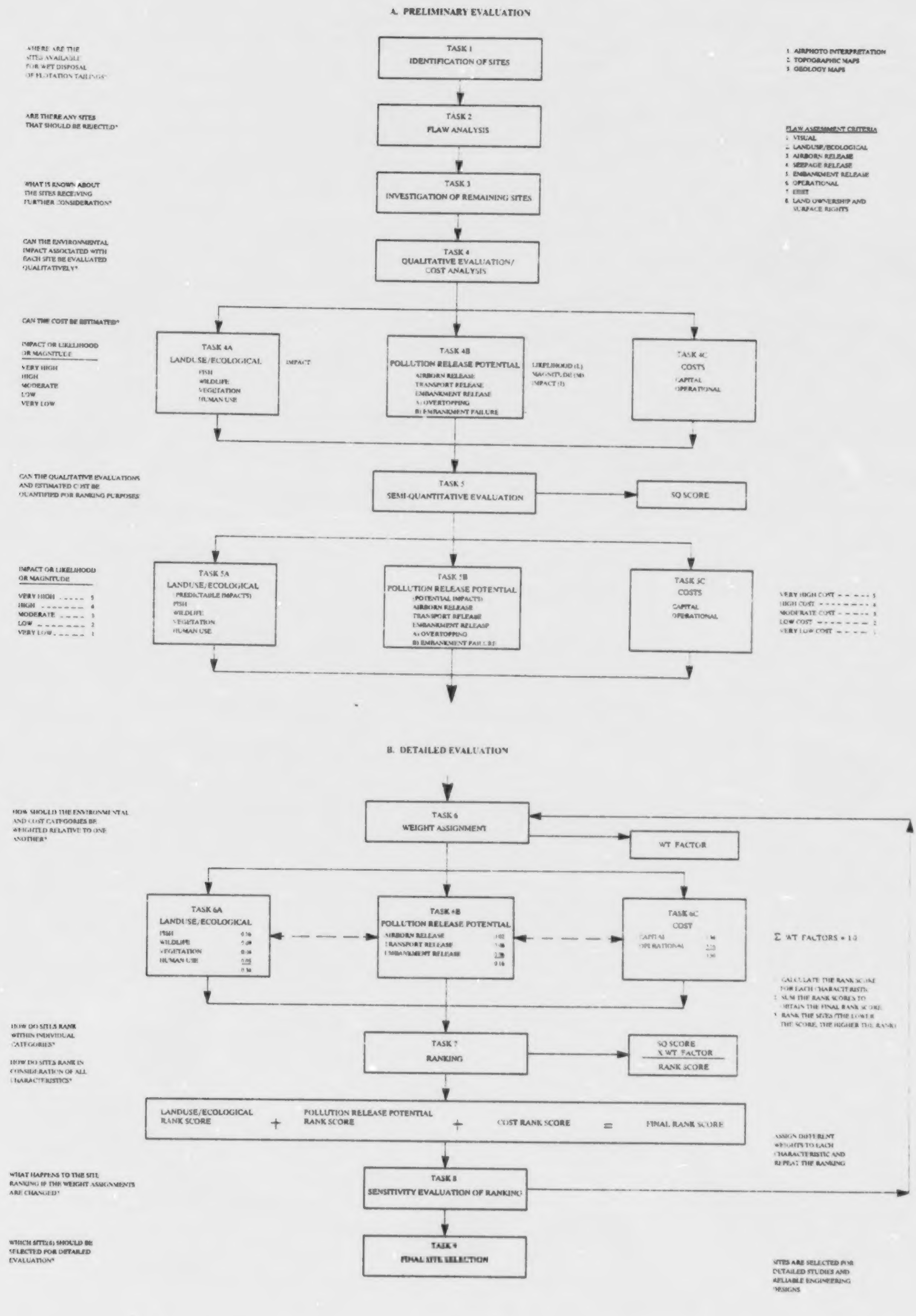

A. PRELIMINARY EVALUATION
WHERE ARE THE SITES AVAILABLE FOR WET DISPOSAL OF FLOTATION TAILINGS?
TASK 1
IDENTIFICATION OF SITES
1. AIRPHOTO INTERPRETATION
2. TOPOGRAPHIC MAPS
3. GEOLOGY MAPS
ARE THERE ANY SITES THAT SHOULD BE REJECTED?
TASK 2
FLAW ANALYSIS
FLAW ASSESSMENT CRITERIA
1. VISUAL
2. LANDUSE/ECOLOGICAL
3. AIRBORN RELEASE
4. SEEPAGE RELEASE
5. EMBANKMENT RELEASE
6. OPERATIONAL
7. COST
8. LAND OWNERSHIP AND SURFACE RIGHTS
WHAT IS KNOWN ABOUT THE SITES RECEIVING FURTHER CONSIDERATION?
TASK 3
INVESTIGATION OF REMAINING SITES
CAN THE ENVIRONMENTAL IMPACT ASSOCIATED WITH EACH SITE BE EVALUATED QUALITATIVELY?
TASK 4
QUALITATIVE EVALUATION/ COST ANALYSIS
CAN THE COST BE ESTIMATED?
IMPACT OR LIKELIHOOD OR MAGNITUDE
VERY HIGH
HIGH
MODERATE
LOW
VERY LOW
TASK 4A
LANDUSE/ECOLOGICAL
FISH
WILDLIFE
VEGETATION
HUMAN USE
IMPACT
TASK 4B
POLLUTION RELEASE POTENTIAL
AIRBORN RELEASE
TRANSPORT RELEASE
EMBANKMENT RELEASE
A) OVERTOPPING
B) EMBANKMENT FAILURE
LIKELIHOOD (L)
MAGNITUDE (M)
IMPACT (I)
TASK 4C
COSTS
CAPITAL
OPERATIONAL
CAN THE QUALITATIVE EVALUATIONS AND ESTIMATED COST BE QUANTIFIED FOR RANKING PURPOSES
TASK 5
SEMI-QUANTITATIVE EVALUATION
SQ SCORE
IMPACT OR LIKELIHOOD OR MAGNITUDE
VERY HIGH ----- 5
HIGH ------- 4
MODERATE ---- 3
LOW ------- 2
VERY LOW ---- 1
TASK 5A
LANDUSE/ECOLOGICAL
(PREDICTABLE IMPACTS)
FISH
WILDLIFE
VEGETATION
HUMAN USE
TASK 5B
POLLUTION RELEASE POTENTIAL
(POTENTIAL IMPACTS)
AIRBORN RELEASE
TRANSPORT RELEASE
EMBANKMENT RELEASE
A) OVERTOPPING
B) EMBANKMENT FAILURE
TASK 5C
COSTS
CAPITAL
OPERATIONAL
VERY HIGH COST ----- 5
HIGH COST -------- 4
MODERATE COST ----- 3
LOW COST ------- 2
VERY LOW COST ---- 1
B. DETAILED EVALUATION
HOW SHOULD THE ENVIRONMENTAL AND COST CATEGORIES BE WEIGHTED RELATIVE TO ONE ANOTHER?
TASK 6
WEIGHT ASSIGNMENT
WT FACTOR
TASK 6A
LANDUSE/ECOLOGICAL
FISH 0.16
WILDLIFE
VEGETATION
HUMAN USE 0.05
0.36
TASK 6B
POLLUTION RELEASE POTENTIAL
AIRBORN RELEASE
TRANSPORT RELEASE
EMBANKMENT RELEASE
0.16
TASK 6C
COST
CAPITAL
OPERATIONAL
Σ WT FACTORS = 1.0
1. CALCULATE THE RANK SCORE FOR EACH CHARACTERISTIC
2. SUM THE RANK SCORES TO OBTAIN THE FINAL RANK SCORE
3. RANK THE SITES (THE LOWER THE SCORE, THE HIGHER THE RANK)
HOW DO SITES RANK WITHIN INDIVIDUAL CATEGORIES?
HOW DO SITES RANK IN CONSIDERATION OF ALL CHARACTERISTICS?
TASK 7
RANKING
SQ SCORE
X WT FACTOR
RANK SCORE
LANDUSE/ECOLOGICAL RANK SCORE
+
POLLUTION RELEASE POTENTIAL RANK SCORE
+
COST RANK SCORE
=
FINAL RANK SCORE
ASSIGN DIFFERENT WEIGHTS TO EACH CHARACTERISTIC AND REPEAT THE RANKING
WHAT HAPPENS TO THE SITE RANKING IF THE WEIGHT ASSIGNMENTS ARE CHANGED?
TASK 8
SENSITIVITY EVALUATION OF RANKING
WHICH SITE(S) SHOULD BE SELECTED FOR DETAILED EVALUATION?
TASK 9
FINAL SITE SELECTION
SITES ARE SELECTED FOR DETAILED STUDIES AND RELIABLE ENGINEERING DESIGNS

Figure 6.1-1 U.S. Site Selection Methodology (after Caldwell and Welsh 1980)

and ranking, but sensitivity checks are carried out to evaluate the importance or otherwise of particular ratings. The final ranking is a summation of three components based on:

- landuse/ecology, (public acceptability)
- pollution release potential, and
- cost.

The two or three highest ranking sites are subjected to detailed evaluation usually involving field investigations.

A systems analysis approach (Vick 1983 and 1984), has been designed to meet the interests of all parties, i.e., the mining company, regulatory agencies, citizen groups and so on. His method is to evaluate alternative disposal strategies systematically step by step as follows:

- definition of objectives,
- formulation of measures of effectiveness,
- definition of alternatives,
- evaluation of alternatives, and
- selection of preferred alternative.

In the Canadian context the definition of objectives and guidelines for siting tailing retention facilities were stated by the Atomic Energy Control Board, (Coady and Henry 1978). But as Vick points out defining an objective is a waste of effort if there is no means of determining whether or not it is being met. He argues strongly for definition of objectives in clear measurable terms.

When picking alternatives tailings disposal sites, the first criteria usually examined is topography and distance from, and elevation with respect to, the millsites. In general it is undesirable during operation to pump tailings to sites much higher than the mill, and preferably the sites should be as close as possible to each other. This has more than simple direct cost considerations, since it minimizes tailings line leaks and failures. Furthermore, if the tailings are situated downstream in the same watershed as the mill, the system is fail-safe, since any escape of tailings from the lines or mill is ultimately washed into the impoundment. Since the constraints on mill site location are usually considerably less than on tailing site selection it is considered advisable that tailings site selection precedes mill site selection. The upstream catchment area determines the flows across the site and hence the long term erosive forces across the site. Foundation conditions and the permeability of the underlying soil and rock strata are usually the second most significant criteria determining the physical stability and seepage characteristics of the site. If acid generation is anticipated, it is preferable to locate the impoundment in a rock or low permeability soil rimmed basin, thus allowing flooding of part or all of the tailings to reduce acid generation.

Knowledge, experience, judgement, common sense, and understanding of regulatory requirements play essential roles in the generation of alternatives, which are quickly narrowed down to a small set of feasible sites. Factors influencing siting are listed in Table 6.1-2.

The evaluation of the final set of alternatives and the selection of the preferred site is made using matrix techniques, sensitivity analysis and allowing for the effects of uncertainty. The matrix array is simply a tabular form listing alternative sites in one column and characteristics, cost, weighing factor or other parameters in other columns so that a visual comparison can be made. Rank-order matrices listing alternatives and objectives can be employed in which an integer rank, say 1 to 3 is assigned to each site to reflect its relative ability to meet the objective according to the measure of effectiveness. Rank ordering can be made more sophisticated by the use of scoring procedures where more data is available. Sensitivity analyses help to highlight subjective elements and to account for differences in value judgements of different evaluators, and uncertainty or risk can be examined in the matrix scoring by resort to probability techniques.

TABLE 6.1-2
FACTORS INFLUENCING IMPOUNDMENT SITING, (VICK 1983)

	Parameter	Effects
(1)	Location and elevation relative to mill	Length of tailings and return-water pipelines Capital and operating cost for pumps
(2)	Topography	Embankment layout Embankment fill requirements Diversion feasibility
(3)	Hydrology and catchment area	Long-term water accumulation Flood-handling requirements
(4)	Geology	Availability of natural borrow types and quantities Seepage losses Foundation stability
(5)	Groundwater	Rate and direction of seepage movement Contaminant potential Moisture content of borrow materials

All this may sound rather elaborate for site selection disposal, but it does help to arrive at an objective decision. The components of the decision making process are laid out systematically and open to scrutiny and challenge by all parties. It is a tool only, but provided that the numbers do not blind overall judgement it is often the single most cost effective design step in the development of a long-term stable, uranium tailings impoundment.

Finally, site characterization and exploration is presented from a geotechnical perspective in the proceedings of a workshop, (ASCE 1978) and, although not directed specifically towards tailings disposal, the contents of the papers and the discussion will be found to be helpful in a broader perspective. The editor's forward contains the following pertinent remarks which are just as applicable to uranium tailing impoundment siting:

> The very process of exploring to characterize or define small scale properties of substrata at construction sites is unique to geotechnical engineering. In other engineering disciplines, material properties are specified during design, or before construction or manufacture, and then controlled to meet the specification.
>
> Unfortunately, subsurface properties cannot be specified. They are unknown before exploration, and intended facilities must be designed to meet expected conditions. Often reality differs form expectation because of inadequate exploration. There is a fundamental difference between specifying and controlling a property and exploring to deduce that property.

The topics discussed in the proceedings include exploration contracts, use of probability and reliability, development of appropriate geophysical devices, use of decision analysis as well as a discussion of research needs.

6.1.3 TECHNICAL APPROACH FOR NEW SITES FOR EXISTING TAILINGS FROM UMTRAP

The remedial action plan calls for stabilization of existing tailings piles, and where this cannot be achieved in place or on site, relocation to an alternative site is required. This is necessary when there are said to be "fatal design flaws" with the existing site such that long-term or cost-effective stabilization is not possible, (DOE - Technical Approach Document 1986). The procedure to be used for selection of alternative sites includes four phases, (DOE 1986a):

- designation of a search region,
- preliminary screening of the designated search region,
- preliminary screening and evaluation of potential areas, and
- identification and evaluation of candidate sites.

Search regions are typically within an 8-kilometer radius of the processing sites.

The preliminary screening involves developing guidelines that eliminate areas unsuitable for tailings disposal. The guidelines are reproduced in Table 6.1-3. Factors are not weighted or ranked, but rule out broad areas from further consideration thus minimizing detailed design work. Although Canadian criteria will differ, lake disposal for example being feasible here, the UMTRAP guidelines serve as a useful checklist.

From lands not eliminated by the preliminary screening no more than three potential areas, defined as being between 15 and 250 ha, are selected. The criteria used for selection are geotechnical, engineering, hydrological and environmental.

Within the selected areas field inspections are conducted to pick no more than three specific sites, ranging between 15 and 40 ha.

The sites are ranked using geotechnical, hydrological, environmental and economic criteria according to 30 site-specific weighted factors. Out of a possible 400 points, the summation of the factor scores (equal to rank multiplied by weight) are determined for each site.

Such rating matrix procedures can be helpful but undue reliance should not be placed on the numerical answer unless the ranking and weighting of each factor can be done with confidence. It is, however, a useful methodology for focusing attention on items in a systematic manner.

6.1.4 IMPOUNDMENT ALTERNATIVES

The basic components of tailings impoundments are:

a) embankment structures (or containment basins)
b) diversion ditches and spillways
c) liners and covers
d) water interception and treatment facilities

Items a), b), c) and d) are discussed in Sections 7.1, 7.2, 7.3 and 7.5, respectively. The layout of control structures are discussed below. The basic components of above-grade impoundments are as shown in sketch plan and section in Figure 6.1-2. Below grade impoundments have similar components except that the embankments to confine the tailings will be unnecessary if the tailings are stored entirely below grade level such as in a mined-out pit.

TABLE 6.1-3
UMTRAP REGIONAL SCREENING GUIDELINES

Characteristic	Definition
Geologic faults	Areas within 1 km of capable faulting as defined by 10 CFR Part 100, Appendix A.
Liquefaction potential	Within 0.4 km of areas having saturated loose sands or visible surface indications of disrupted drainage or broken ground.
Landslides	Areas within 0.4 km of visible indications of slope instability.
Erodable soils	Areas of known highly-erodable soils.
Slopes and escarpments	Slopes steeper than 33 percent grade, or areas from the top of an escarpment in excess of 3 m in height established by the intersection of the ground surface with a plane inclined at a 20° angle from a horizontal plane passing through the toe of the escarpment, or 30 m, whichever is greater.
Water bodies	Lakes, ponds, reservoirs, rivers, or perennial streams.
Wetlands	Wetlands as defined by the U.S. Fish & Wildlife Service or U.S. Army Corps of Engineers.
Floodplains	100-year floodplains as defined by the U.S. Department of Housing & Urban Development, or within 0.2 km of a stream centreline.
Aquifers	Areas directly overlying, or recharge areas for, sole-source aquifers or aquifers containing potable water; unless, the ground waters in those aquifers are hydrologically isolated from downward migration of contaminants by low permeability geologic formations or strata.
Surface drinking water supplies	Areas within one mile of surface drinking water supplies.
Communities	Areas within one mile of community limits (legal boundary).
Mineral resources	Significant known recoverable resources of oil, gas, coal, and other minerals (except uranium and gravel).
Subsidence areas	Within 0.4 km of areas susceptible to subsidence by natural or man-made causes.
Transportation and communication corridors	Areas within the rights-of-way of state, Federal, and county roads.
Archaeological & historical resources	Within 30 m of archaeological or historical districts and sites listed on the National Register of Historic Places.
Prime farmlands	Areas designated by the Soil Conservation Service as being within the Class II soil capability classification.
State & National Parks	Within 0.4 km of parks and monuments under Federal, state, or local jurisdiction.
Wilderness & natural areas	Within 0.4 km of Wilderness Areas, Wilderness Study Areas, Natural Areas, areas of critical environmental concern, and roadless areas as identified by the U.S. Forest Service, or Bureau of Land Management.
Wildlife refuges	Within 0.4 km of wildlife refuges and designated migratory bird feeding areas.
Critical habitat	Within 0.4 km of designated critical habitat for threatened or endangered species, fishery resource areas, and botanically and geologically sensitive areas.

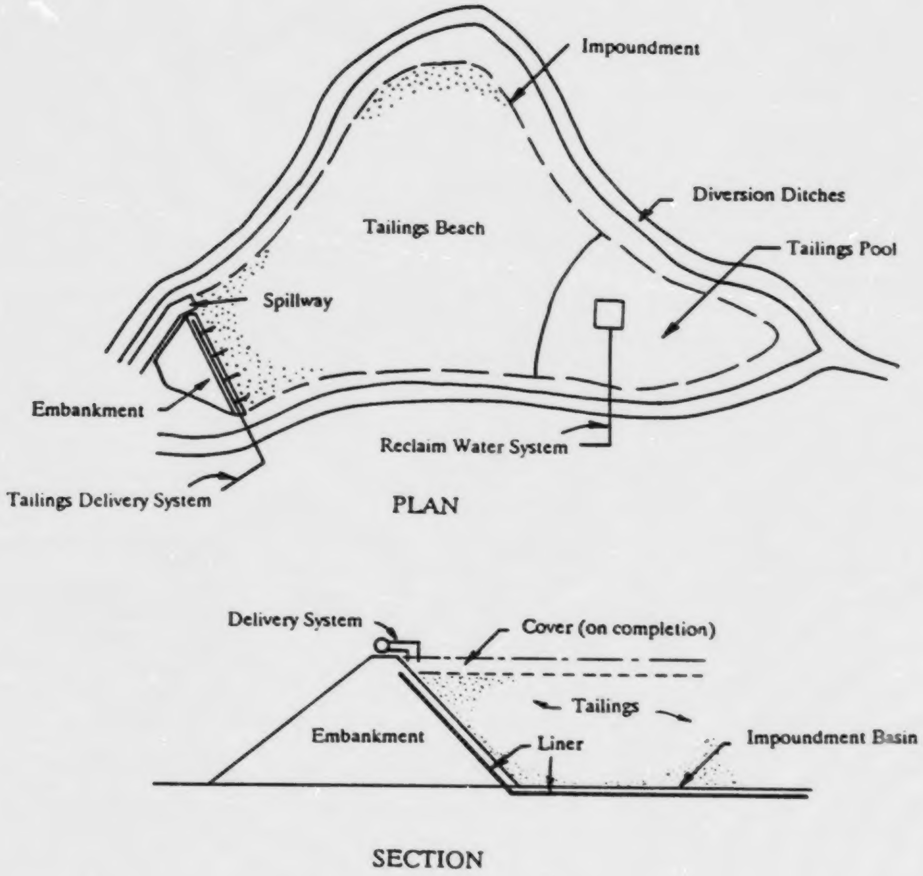

Impoundment
Diversion Ditches
Tailings Beach
Tailings Pool
Spillway
Embankment
Reclaim Water System
Tailings Delivery System
PLAN
Delivery System
Cover (on completion)
Tailings
Embankment
Liner
Impoundment Basin
SECTION

Figure 6.1-2 Basic Components of Uranium Tailings Impoundments

The principal methods of disposal are:

- valley dam
- ring dyke
- mine-pit

They are shown diagrammatically on Figure 6.1-3 (adopted from Robertson et al 1978). Whereas the valley dam impoundment is usually a feasible, economical type in hilly or undulating terrain, the ring-dyke containment is needed in flat terrain lacking natural depressions of any appreciable size.

In addition to the above impoundments it is sometimes appropriate to return a portion of the tailings to the underground mine workings.

Other alternatives can be considered such as a specially dug pit impoundment, underground mine and lake impoundments. The last alternative, of disposal in lakes, is a viable alternative in Canada, although considerable site specific investigation is needed. Placing tailings in lakes means that free oxygen available to oxidize the tailings is reduced thus minimizing dissolution of the radionuclides. In time natural sedimentation should form a cover over the tailings thus providing additional protection to the environment.

Above-grade impoundments should make maximum use of existing topography. Containment should be achieved by both the embankment and liner being of low permeability. The liner may be a natural geological liner.

An assessment of the more common disposal alternatives should take into consideration the design aspects noted in the following sub-sections.

6.1.4.1 Valley Dam Impoundments

Since valley dams are in topographically low areas, visual impact tends to be minimal, but surface water runoff from the drainage basin is automatically collected in the impoundment area. Long-term seepage and erosion control are therefore required to divert flows around the impoundment area. Ongoing maintenance of such diversions is a serious drawback.

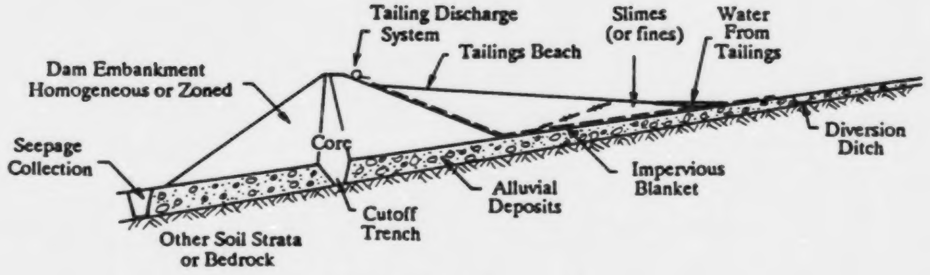
As these impoundments are located in water courses, rapid transport of any spillage or seepage into the river system can occur.

Deep alluvial deposits commonly occur in valley floors. The horizontal permeability of such deposits can be high allowing lateral migration of seepage water, and water diversion ditches and/or liners are sometimes necessary.

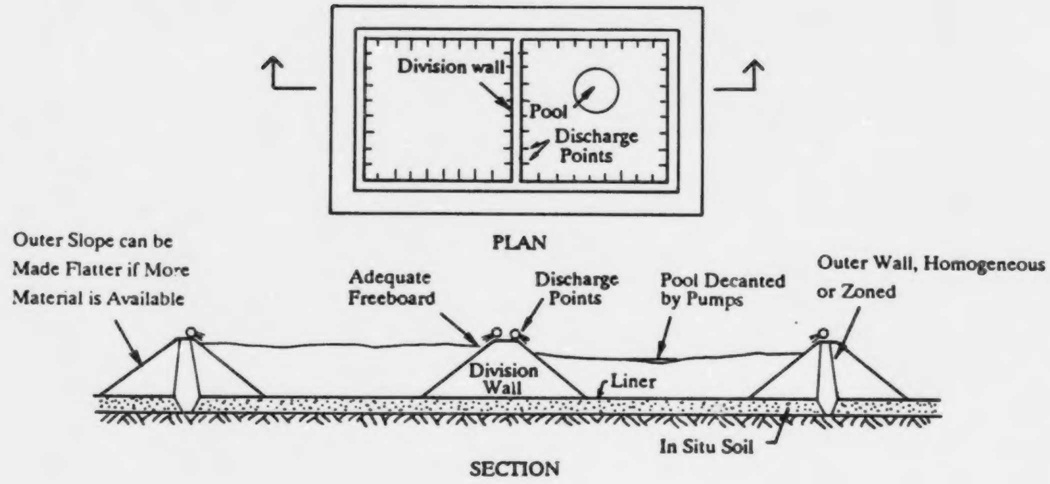
Valleys often form because of some underlying geological feature, such as a fault or shear zone, which may itself be a zone of higher permeability. Groundwater is usually shallowest in the valley floor area, and thus seepage from the impoundment has only a relatively short distance to travel before it joins the groundwater.

These disadvantages, associated largely with the groundwater considerations, are offset by the economics of construction, since a high storage to embankment volume ratio usually results.

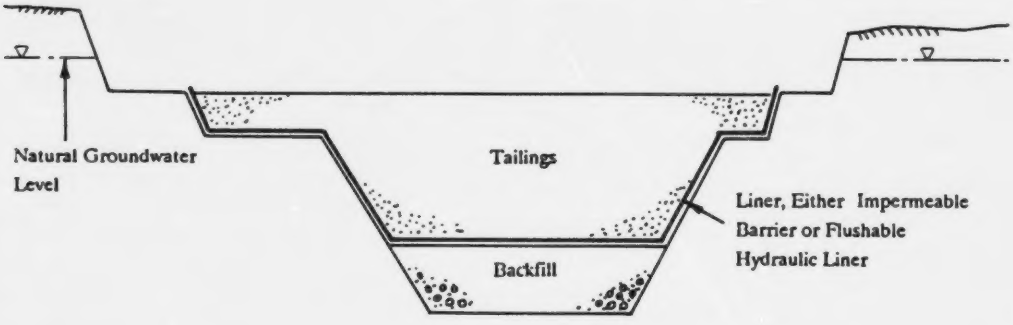
Since the valley forms three sides of the impoundment, only a relatively short dam wall is required to complete the impoundment, but for a given volume of tailings the dam may need to be high, resulting in large hydraulic gradients.


Tailing Discharge System
Tailings Beach
Slimes (or fines)
Water From Tailings
Dam Embankment Homogeneous or Zoned
Seepage Collection
Core
Diversion Ditch
Impervious Blanket
Alluvial Deposits
Cutoff Trench
Other Soil Strata or Bedrock

a) Valley Dam Impoundment


Division wall
Pool
Discharge Points
PLAN
Outer Slope can be Made Flatter if More Material is Available
Adequate Freeboard
Discharge Points
Pool Decanted by Pumps
Outer Wall, Homogeneous or Zoned
Division Wall
Liner
In Situ Soil
SECTION

b) Ring Dyke Impoundment


Natural Groundwater Level
Tailings
Backfill
Liner, Either Impermeable Barrier or Flushable Hydraulic Liner

c) Disposal in a Mined-Out Pit

Figure 6.1-3 Typical Types of Impoundments

Because of the shape of the valley, tailings depths are shallow along the three natural sides becoming progressively deeper towards the middle. The mean tailings depth is generally fairly low and the final surface area high. This increases the surface area exposed for seepage and wind erosion and the volume of the cover required for stabilization.

The shape of the valley floor is often irregular and installation of liners may be difficult. Where tailings line discharges are used along the crest of the embankment, soft slimes usually deposit along the outer edges of the basin, creating differential settlement and placement problems with covers. With such deposition the pond is located against the valley sides and may result in high seepage rates into the underlying soil strata.

The shape of the valley normally restricts seepage and surface flow to a known path or channel generally directed down the centre line of the valley, and measures to minimize or return seepages are relatively simple. Typical valley dam impoundments in the Elliot Lake area are shown on Photos 6.1-1 and 2.

6.1.4.2 Ring Dyke Impoundments

Ring dyke impoundments are formed by constructing cells with perimeter enclosing embankments, and they may be constructed in single or multiple stages. Where the terrain is more undulating they may be formed by a succession of valley dams embankments linked by low saddle dykes, see Photo 6.1-3.

Rectangular or irregular shapes are used together with internal partitions to sub-divide the impoundments into two or more compartments.

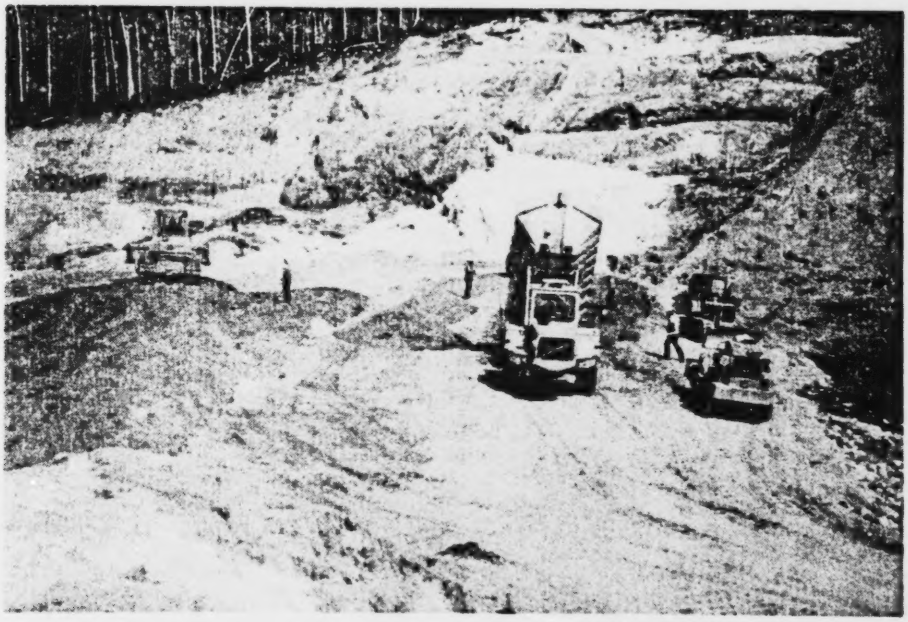


Photo 6.1-1 Tailings dam construction, Elliot Lake, Ontario.

Photo 6.1-2 Completed tailings dam, Elliot Lake, Ontario.

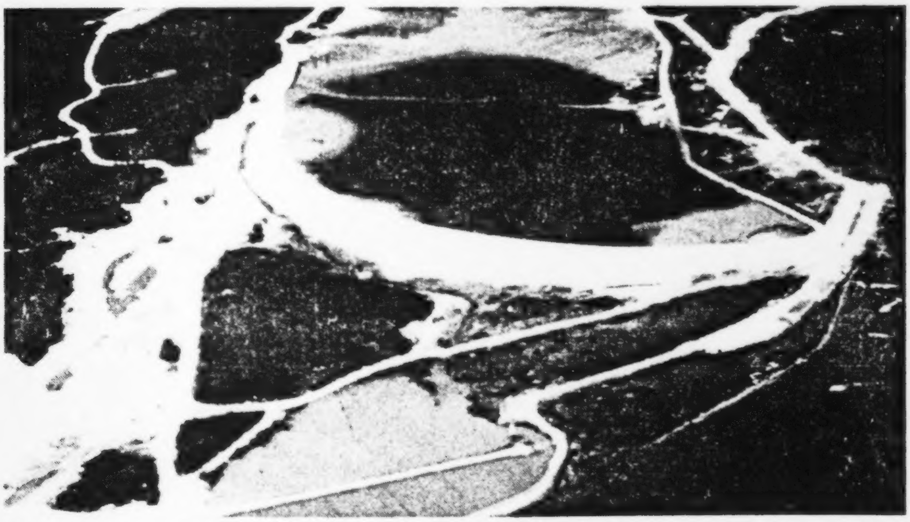


Photo 6.1-3 Dyked valley disposal at Rabbit Lake, Saskatchewan. Decant ponds are in foreground. Tailings were spigotted from dykes and decantation was from a floating barge.

Photo 6.1-4 Pervious surround of sand and crushed waste rick, in-pit disposal, Rabbit Lake, Saskatchewan

Because ring dykes are generally located in flatter areas than valley dams they have a greater flexibility in location.

Ring dykes have a lower maximum embankment height for a given volume of tailings compared with valley dams.

The long embankments required for ring dykes may result in an increased risk of embankment failure and/or seepage losses through the wall and the foundation.

The relatively low embankment height reduces problems of re-establishment of drainage when tailings are covered during abandonment preparation.

Ring dykes can commonly be close to the mine, thereby allowing for easy use of mine waste materials for construction and for tailings rehabilitation. The ratio of catchment area to storage area in a ring dyke can be minimized and the risk of overtopping due to flooding can be virtually eliminated.

Ring dykes can be away from streams, thereby reducing the risk of erosion or damage due to flooding. Furthermore seepage from the impoundment is not released directly into the streams. Pathways for potential contamination of surface waters are generally longer than for valley dams, and greater time may be available to implement remedial measures if needed. The regular shape and the minimization of the catchment area allows control over tailings placement and beach development, tailings solids buildup, evaporative drying and stored water depth.

Ring dykes are often located near the crest of flat ridges or higher ground where the depth to the water table is appreciable. This tends to increase the time required for contaminants to enter the environment. In regions of high rainfall, the location of impoundments on high ground exposes tailings to conditions favourable for water diversion and evaporation of pond water, but on the other hand such conditions inherently favour wind erosion.

The storage to embankment volume ratio of ring dyke impoundments are usually low, so that considerable quantities of material are needed for the embankment dykes. However, if earthfill is to be used for dyke building and suitable material exists within the confines of the pond the economics become more favourable. This is because of the short haul distances involved and the additional storage volume achieved by excavation within the impoundment.

6.1.4.3 Mine-Pit Impoundments

Worked-out mine pits can be used for tailings disposal. The method varies considerably depending on the climate, the depth to and variability of groundwater, the proximity to streams, the susceptibility of the pit to flooding, the permeability of the wall rocks in the pit, the mining program adopted, whether wet or dry tailings management is practiced, and the characteristics of the tailings. It is clearly site-specific and must be designed in accordance with the conditions prevailing at the site, particularly groundwater.

The technique depends on the mining program adopted. It can be used where there is an existing worked-out mine pit, or where the orebody is mined completely before milling commences.

Where a low overburden stripping ratio exists, or where the pit is located in sloping topography the tailings volume may exceed the usable storage volume in the pit.

However, depending on the potential for erosion of the impoundment cover, greater depths of burial can provide greater assurance of confinement on abandonment. Furthermore visual impacts and air pollution are minimal if not eliminated, and increasing pit depth usually minimizes the surface area of the tailings and consequently the areal extent of the cover.

Either water or soil cover may be applicable. Rehabilitation of the impoundment may be difficult if saturated tailings have been deposited in the pit. In such cases soil covers may be subject to large deformations due to post closure settlement.

Dykes are not usually required and hence the risk of failure from this source is minimized, but instability of the pit wall may affect the integrity of any liner, and where lining of the pit is necessary, flatter excavation of the pit slopes may be required to facilitate liner installation and to ensure liner stability. The resulting requirement for a wider pit may have unacceptable economic consequences. Where a liner is required to retard seepage from the pit, it can also retard drainage of water through the pit walls, leading to possible instability. This problem is overcome where tailings can be placed above the water table. The alternative is to use a hydraulic liner (Matich and Tao 1984) as in the Collins Bay scheme in Northern Saskatchewan, in which tailings are deposited in the abandoned Rabbit Lake pit, see Photo 6.1-4. The "liner" is a pervious-surround, granular filter placed against the pit wall. The naturally occurring, high groundwater table provides a hydraulic barrier to seepage by preventing the establishment of a hydraulic gradient across the deposit. During tailings placement, a hydraulic gradient exists between the interior of the tailings mass and the permeable surround. This hydraulic gradient must dissipate before contaminated water flow from the tailings mass to the permeable surround ceases and treatment of water drained from the permeable surround can be discontinued.

A thorough knowledge of the climate, groundwater fluctuations, rock mass structure and permeability, and transmissivity is necessary for the design of a mine-pit impoundment.

Uranium-enriched ore zones may be unevenly scattered through the mineralized region. Since pit boundaries are frequently determined by mining economics and not necessarily by mineralization limits, the tailings may cover future ore reserves. Re-mining of the area may be difficult if saturated or wet disposal techniques are used. Impoundments of dry or semi-dry tailings could be more readily re-mined.

The use of mined-out pits may complicate future underground mining operations.

Specially dug pit impoundments are a hybrid with characteristics of both ring dykes and mine-pit impoundments. As in the ring dyke technique the materials excavated to form the pit may be used to form the retaining embankments. The main difference between the two is that in the specially dug pit impoundment most of the tailings will be replaced below ground surface, whereas for the ring dyke impoundment the only portions of the tailings stored below the original surface are those contained within the interior borrow area. With increasing excavation depths the technique becomes similar to the mine-pit impoundment.

The major disadvantage of digging a special pit are the excavation costs.

An alternative commonly used with underground mining operations is to separate the coarser sand fraction from the slimes and use it for mine fill. This reduces tailings storage volume requirements, but the disposal of the slimes is usually more difficult. Furthermore, underground disposal of the coarse fraction of the tailings does not reduce the radioactivity in the surface deposited slimes appreciably. Ventilation problems caused by radon gas from the mine fill can also arise if the mine is in operation, although the experience to date in Canada has been good.

6.2 TAILINGS DEPOSITION

During the past two decades considerable advance has been made in understanding the physical and chemical processes that are active in tailings deposits. It has been recognized that alternative placement methods and impoundment operating procedures result in deposits with substantially different engineering properties, and advantage has been taken of these differences to develop alternative impoundment construction methods suited to different tailings types, sites, climatic conditions and performance criteria.

The characteristics of a tailings deposit depend on:

(i) the properties of the tailings solids (grain size and shape, specific gravity, mineral composition etc.),

(ii) the structure assumed by the solid grains during deposition (density, alignment etc.),

(iii) the presence or absence of water in the pore spaces between the grains,

(iv) whether the water in the pore spaces is frozen and

(v) the stress history to which the tailings have been subjected.

These factors determine the properties of the tailings which in turn control their engineering behaviour with regard to seepage, settlement and stability. The properties of the tailings solids are largely determined by the nature of the ore milled (mineral composition) and the milling process required to extract the uranium economically. Tailings deposit properties can be substantially modified by controlling the conditions which determine factors (ii) to (v) above. This section examines some of the methods of tailings deposition that may be used to control these items and achieve deposits with properties that are more favourable for the stable containment of the tailings.

6.2.1 PROPERTIES OF TAILINGS

In this sub-section the basic properties of uranium tailings, and their effects on the engineering properties of the deposit are reviewed. The values for the various tailings properties quoted may be compared with typical values applicable at Elliot Lake and Saskatchewan as listed on Table 3.3-1 and 2 in Section 3.3.

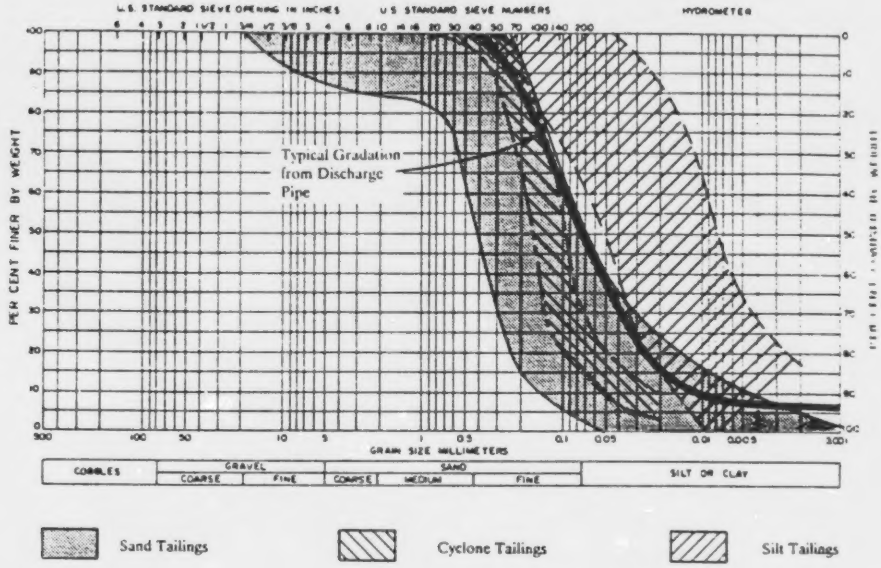
6.2.1.1 Grain Size and Shape

(a) Ground ore particles

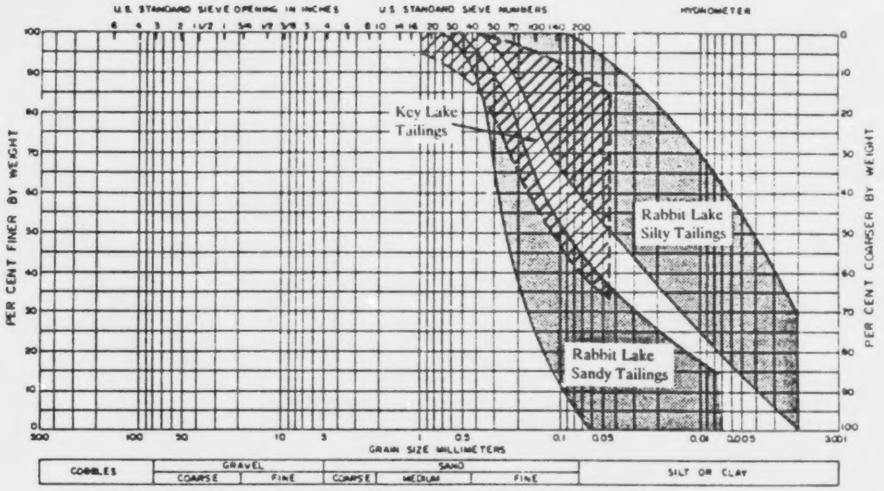
During milling the ore is ground to a limiting particle size to facilitate liberation of the uranium. The resulting distribution of particle sizes depends partly on the grinding method but largely on the nature of the ore. This size distribution is modified during the additional stages of milling as a result of chemical effects on the ore grains.

Hard, chemically stable host rocks, such as the quartzites encountered in the Elliot Lake mines undergo relatively little chemical degradation and the resulting grain size distribution in the tailings is largely that induced by the grinding. Particles are predominantly small hard rock fragments, though they may have been reduced to "clay" sizes. In the Elliot Lake mines the ore is ground during milling until typically 50% is finer than 75 mm. Thus the tailings are in the size range of silty sands to sandy silts. Typical gradings for such tailings are indicated in Figure 6.2-1. The equidimensional nature of the clay sized rock flower, as distinct from the platy nature of true clay minerals, results in increased permeability and better consolidation characteristics than might be anticipated from materials with similar gradings containing true clay minerals. Such tailings are non-plastic with relatively low Liquid and Plastic Limits (refer Table 3.3-1).

The ores from the Athabasca sandstones in Saskatchewan contain a significantly greater percentage of true clay minerals than the quartzitic Elliot Lake ores. Where clay contents are high the platy clay minerals result in reduced permeability and low density compressible deposits. An example of the



ELLIOT LAKE



SASKATCHEWAN

Figure 6.2-1 Typical Tailings Gradations

grading for such tailings, from the Saskatchewan Rabbit Lake site, is shown in Figure 6.2-1. The Liquid and Plastic Limits and Plasticity Index are commensurately greater (refer Table 3.3-2).

Additional grain size modification occurs as a result of the incorporation of other solid particles, principally in the form of precipitates resulting from the neutralization of the acidic uranium stripping agents. Lime neutralization of sulphuric acid, for example, produces gypsum. The gypsum precipitates in the form of fine needle shaped crystals which interlock. These needle shaped particles may fuse together at contact points forming a fairly rigid lattice. The resulting deposits have low density. Gypsum crystals tend to deform under stress and, with time there is some resolution and recrystallization of the needles. A gypsum rich tailings deposit, such as the Saskatchewan Key Lake site, tends to exhibit low solids densities which are volumetrically unstable, compressing with time. An example of grading curve for a gypsum rich tailings (Key Lake) is provided in Figure 6.2-1. Such grading curves should be interpreted with caution since they do not reflect particulate size distributions in the true sense, being dependant on the test method. The presence of precipitates makes testing difficult, and the properties of such tailings may be expected to change significantly with time. The long term behaviour of gypsum rich tailings has been fairly extensively studied by Wrench and Blight 1985 and Wrench 1987. Reference to their work will be of considerable benefit for the development of appropriate techniques for gypsum rich tailings in Canada.

During tailings deposition segregation of the tailings often occurs along the flow path, with coarser sands being deposited closest to the discharge locations, and the fines or slimes being transported to the vicinity of the pond or decant. Thus the grading of the deposit, at any one location in the tailings impoundment, is not normally the same as that at the discharge point. This often results in concentrations of similar sized grains (gap-graded deposits) in various locations of the impoundment.

6.2.1.2 Density and Void Ratio

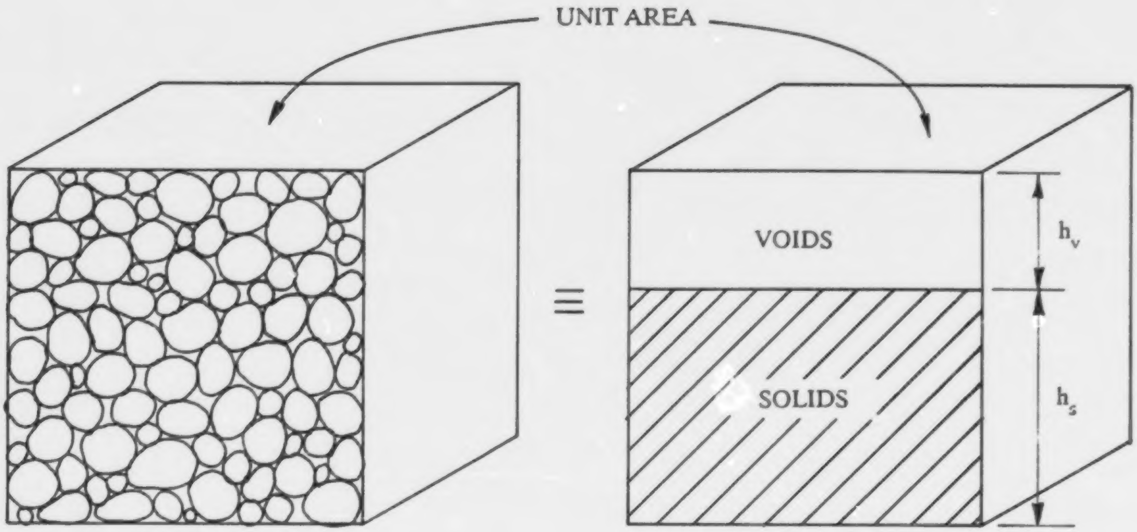
A definition for void ratio, dry and total densities, and moisture content is provided in Figure 6.2-2. Note that moisture content can be, and is commonly, expressed differently by metallurgists and geotechnical engineers. Care must be exercised to define which term is being used whenever moisture contents are given. The engineering term is used in this manual.

The void ratio is the ratio of volume of voids, not occupied by tailings solids, to the solids volume. The void space is that volume which can be filled by air or tailings effluent. It represents that volume from, and through, which seepage flow can occur. The tailings solids are, for practical purposes, incompressible and during consolidation the tailings particles move into a closer packing reducing the void ratio. Thus void ratio is a fundamental property of interest, influencing the seepage and consolidation characteristics of the tailings.

Generally the coarser and the more evenly graded the tailings (well-graded distribution of coarse and fine particles) the more readily they settle to a relatively low void ratio. Tailings with a high percentage of platy clay minerals and those with gypsum crystals often develop a loose "house of cards" type structure and generally have higher void ratios. Tailings in the pool zone tend to display higher void ratios than those deposited in the beaches.

Well-graded particulate tailings such as the quartz rich materials at Elliot Lake generally produce deposits with relatively low void ratios. Clay-rich deposits, such as some of the Saskatchewan ores tend to have higher void ratios, with the highest void ratios being associated with the high gypsum tailings of the newest high-grade nickel arsenic ores of Saskatchewan. Examples of void ratios at the various deposits are given in Tables 3.3-1 and 3.3-2 in Chapter 3.

The dry density of the tailings deposit is related to the void ratio through the density of the solid tailings particles. This relationship is defined in Figure 6.2-2. The greater the dry density (the lower the void



$$\text{Void ratio} = \frac{\text{Volume of Voids}}{\text{Volume of Solids}} = \frac{V_v}{V_s} = \frac{h_v}{h_s}$$

$$\text{Dry Density} = \frac{\gamma_s h_s}{(h_s + h_v)}$$

γ_s = specific gravity of solids

γ_w = specific gravity of water

$$\text{Total (saturated) Density} = \frac{V_s h_s + V_v \gamma_w}{(h_s + h_v)}$$

$$\text{(Saturated) Moisture Content} = \frac{\gamma_w h_v}{\gamma_s h_s}$$

Engineering term

$$\text{(Saturated) Moisture Content} = \frac{\gamma_w h_v}{\gamma_s h_s + \gamma_w h_v}$$

Metallurgical Term

Figure 6.2-2 Definition of Density Void Ratio and Moisture Content

ratio) the lower the volume required to store a given tonnage of tailings. Maximizing the density (minimizing the void ratio) is therefore a desirable effect at all tailings deposits.

6.2.1.3 Consolidation Characteristics

Freshly deposited tailings initially have a very high void ratio. If they are subsequently subjected to compressive stresses due to additional incumbent layers of tailings (or desiccation stresses as discussed later) or cover layers, they consolidate. The amount they consolidate depends on the initial void ratio and the consolidation characteristics of the tailings. Basic texts on consolidation mechanisms are provided in many soil mechanics textbooks (Terzaghi & Peck 1967). A through review of consolidation theory, and its applicability to uranium tailings is provided by Geocon 1986. The amount tailings consolidate for a given stress change is described by the Compression Index, C_c, which is a dimensionless constant defined as the slope of the void ratio/pressure line on a semilogarithmic plot. Typical compression indices for some Canadian tailings are provided in the tables referred to in Chapter 3.

Recent studies, however, have indicated that the time rate of consolidation in a tailings impoundment is not well-represented by classical (Terzaghi) consolidation theory. Instead consolidation according to finite strain theory (Schiffman 1980, Carrier and Bromwell 1983, Geocon 1986) provides a more realistic model. This latter model results in considerably increased estimates of drainage and consolidation rates.

Geocon 1986 have undertaken a detailed evaluation of the parameters effecting consolidation and the resulting settlement predictions for the various types of uranium tailings deposits typical for Canada. Settlements after abandonment over the sand beaches and pond zones vary from centimetres to metres depending on the anticipated conditions of drainage, dessication and cover loads. Consolidation and settlement of U.S. uranium tailings have been evaluated elsewhere (Nelson et al 1983, Fayer and McKeon 1984, and Fayer 1985).

During consolidation, water is squeezed out of the tailings voids. The rate at which consolidation can occur depends on the rate at which water can be squeezed from the tailings. This in turn depends on the permeability, which is considered in the next section. With the very low permeabilities associated with some tailings slimes, the rate of consolidation is such that it may take tens of years before settlement is complete. Similar slow consolidation rates are applicable to the fine gypsum rich tailings associated with the Generic Saskatchewan Semi-Dry site.

Should partially saturated conditions be achieved in the tailings, the interstitial water can be squeezed into the volumes occupied by air allowing rapid settlement.

Where the tailings are frozen, drainage is restricted and therefore the tailings consolidate little unless they thaw.

Consolidation is stress history dependent and for each tailings sample there is a void ratio, effective stress relationship (Blight and Steffen 1979). Effective stress increases leading to consolidation can result from any of the following:

(i) Additional layers of incumbent tailings.

Generally the higher the initial void ratio the greater the density increase under increased loading. Thus slimes tend to consolidate more than sands for the same stress change. Full consolidation occurs only after all excess pore water pressures have dissipated, allowing the full effective stress to act on the tailings grain structure. Excess pore pressure dissipation is time dependent, and is a function of the drainage path length. Figure 6.2-3 shows typical changes in density at increasing depth in tailings deposits. Settlement continues for a period

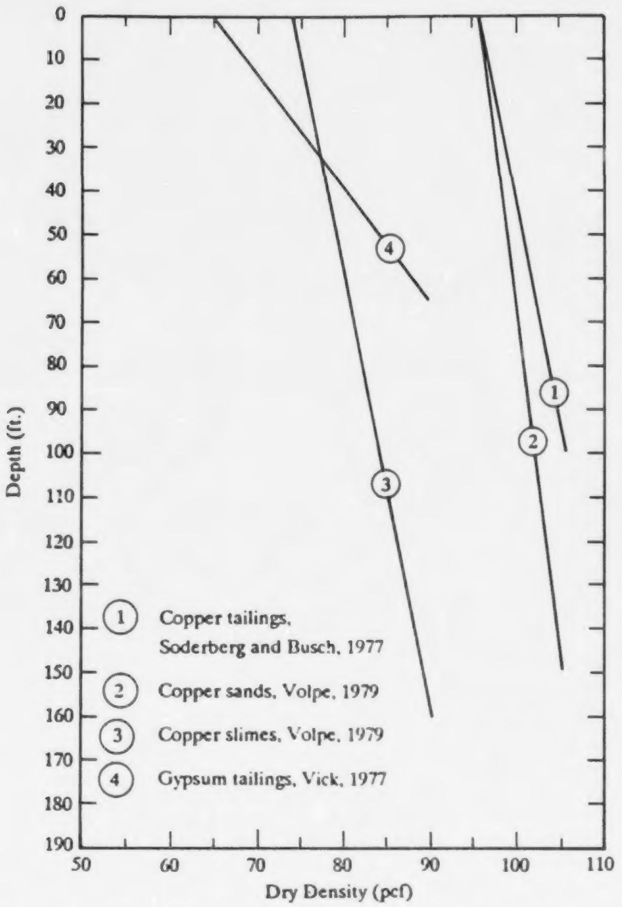


Figure 6.2-3 Increase in Average In-Situ Density with Depth (after Vick 1983)

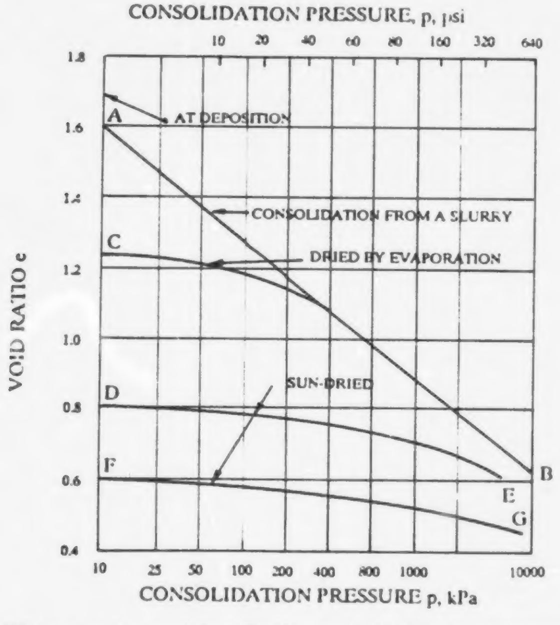


Figure 6.2-4 Effect of Evaporation and Sun-Drying on Void Ratio and Consolidation Characteristics of Gold Tailings Slimes (Blight and Steffen 1979)

following impoundment closure as a result of continued dissipation of pore pressure. The placement of cover layers results in further loadings on the tailings and additional settlement. Geocon 1986 have predicted settlements, after closure, from a few centimetres to about 2 metres over beaches and pond zones respectively for most Canadian tailings deposits. During the period of settlement, tailings water is squeezed from the tailings mass. While this flow rate is appreciable it is necessary to maintain surface and groundwater quality protection measures.

(ii) Drawdown of water table due to underdrainage.

Should any drawdown of the water table occur the effective stresses in the tailings increase, resulting in very substantial settlements, particularly in the region of the slimes pond. For highly segregated tailings deposits, differential settlements may be large, and, if they occur after the tailings impoundment surface has been contoured and covered, drainage patterns will be disrupted and cover layers will crack.

The increased density resulting from drainage decreases the volume of the tailings and increases the capacity of the impoundment.

(iii) Pore suction due to evaporative drying.

The high pore suctions resulting from evaporative drying to low moisture contents is well documented and results in the consolidation and cracking of surficial tailings layers. This method of dewatering and consolidation is exploited to advantage for the creation of the consolidated drained zone of the outer portion of the retaining embankment in the paddock construction system, as discussed later. Large increases in effective stress and the resulting void ratio reductions occur (Blight and Steffen 1979). The effects on void ratio of evaporative drying and desiccation by sun-drying are shown on Figure 6.2.4.

Any such evaporative compaction in the impoundment results in an increase in tailings density, a decrease in volume and increase in the capacity of the impoundment. Thus, where climatic conditions permit, it is advantageous to minimize the tailings pond size and maximize the beach area, thus maximizing evaporative compaction and the advantages to be gained from it.

(iv) Frost action

Freezing of tailings prevents consolidation and drainage for as long as the tailings remain frozen. In northern Canada large accumulations of frozen tailings have occurred under the beach areas of annually layered deposits. Such an accumulation of frozen tailings occurs in the northern section of the Rabbit Lake tailings impoundment (Geocon 1986). On thawing the low density frozen tailings consolidate resulting in large surface settlements. Such settlements disrupt surface drainage and covers. The zones under the pond do not freeze.

Cycles of freezing, and thawing have two effects. On freezing, water is drawn from the tailings pore spaces and forms ice crystals and lenses, which separate the tailing solids. Thus the tailings solids are consolidated between ice-filled channels. On thawing, these channels permit rapid drainage of fluids resulting in an effective increase in the tailings mass permeability. Some of these channels close as the thawing tailings slump under the incumbent loads. For gypsum-rich tailings, the frost induced consolidation may exceed the consolidation due to evaporation, (Knight and Piesold 1986). For tailings subjected to frost action the overall tailings permeability remains considerably higher than for unfrozen tailings consolidated due to equivalent stresses from loading. This modification of the tailings permeability renders modelling using laboratory determined permeability coefficients questionable.

Frost effects on surficial layers of tailings (and cover soils) results in an increase of the surface permeability and consequently an increased infiltration rate. This is important if surface infiltration is to be minimized to reduce leaching and contaminated seepage. Figure 6.2-5 shows the estimate by Geocon 1986 of settlement, and the time period over which it will occur, for the Rabbit Lake tailings impoundment assuming full evaporation and a cover constructed immediately following tailings deposition. The large settlement over the slimes pond is apparent, though it should be recognized that the slimes, sands and transition zones will be more variable than assumed. The dramatic effect of frozen tailings is apparent. Should these tailings thaw then very large settlements can be anticipated as a result of the very high void ratios of the frozen tailings. Contrary to the assumptions in Geocon 1986, the frost susceptability work done for the appendix to this document suggests that such thawing and settlement will occur.

6.2.1.4 Permeability

Permeability of loose uniform sands is approximately related to the grain size according to Poiseuille's Law and can be determined by the following equation by Hazen (Terzaghi and Peck 1967).

$$k = 0.01\, D_{10}^{2}$$

where, k is the permeability of the material in m/s,

D_{10} is the diameter in mm of the particle size at which 10% of the material is smaller.

More recently an alternative expression has been proposed which has been found experimentally to apply to dense sands and gravels (Sherard et al 1984):

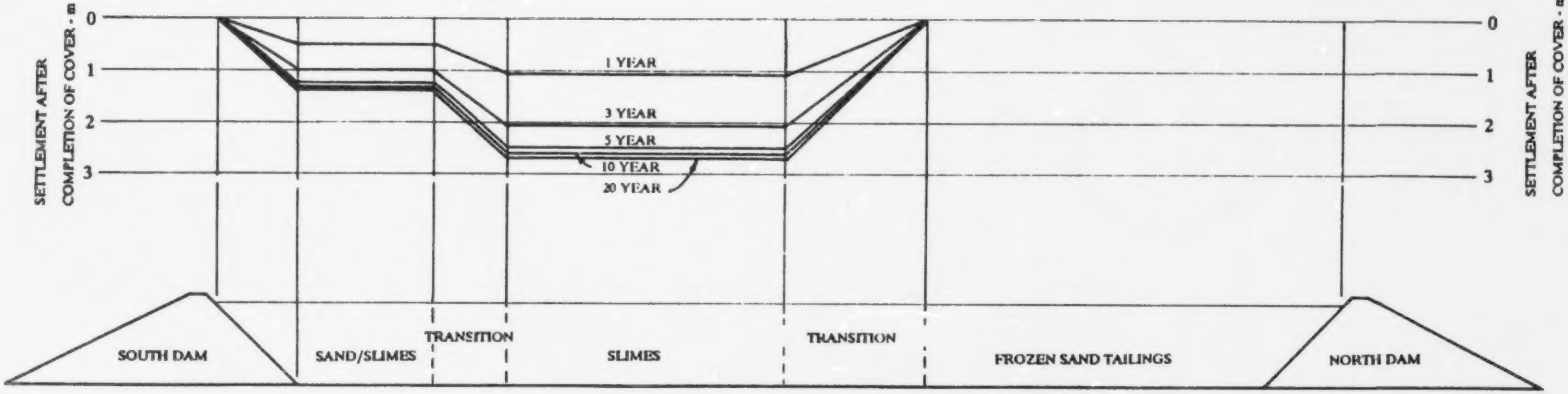
$$k = 0.0035\, D_{15}^{2}$$

D_{15} is the diameter in mm of the particle size at which 15% of the material is smaller.

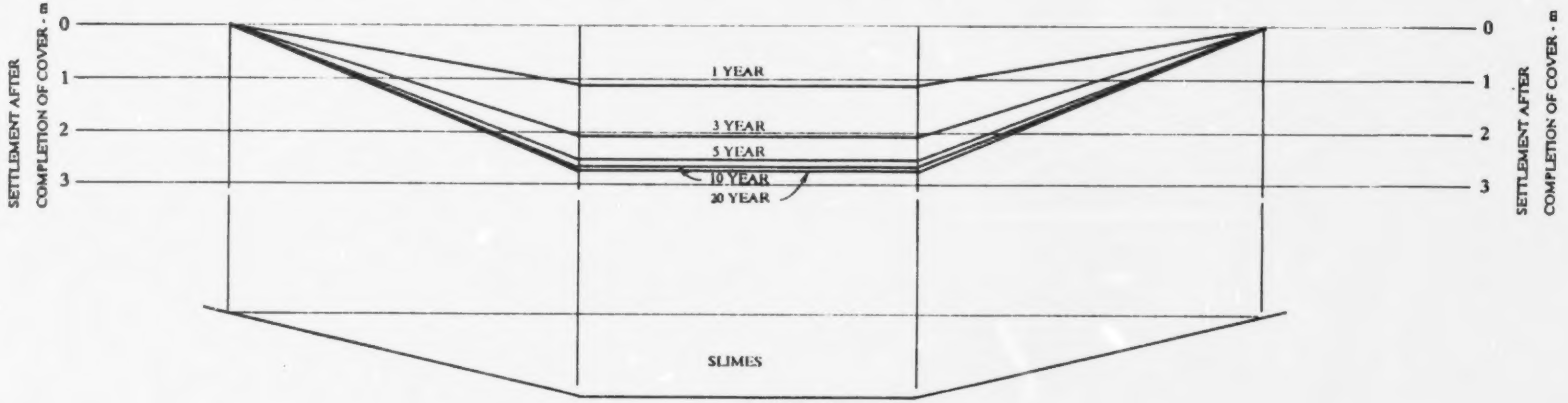
Thus the permeability of the tailings increases approximately as the square of the particle size in the finer fraction of the tailings. This relationship is only approximate as the permeability is effected also by the shape of particles and void ratio. Permeabilities are generally less if the particles are platy, such as for clays, and it reduces with decreasing void ratio. Thus the permeability of the fine slimes zone in a tailings pond is typically two or more orders of magnitude less permeable than the sand beach zones. Permeabilities also decrease towards the base of the impoundment where the tailings are more consolidated. Thus the permeability in a tailings impoundment may range from about 1×10^{-9} m/sec at the base under the pond zone to 1×10^{-7} m/sec on the sandy beach. These large permeability differences result in huge differences in the consolidation, seepage and infiltration rates.

Layering in the tailings can result in successive layers of finer and coarser tailings with permeabilities that differ by two orders of magnitude or more. These layers tend to be flat lying as a consequence of their formation on beaches. An anisotropy results in which the permeability parallel to the layers is approximately that of the more permeable layers, while that normal to the layers is approximately that of the low permeability layers. This can result in a horizontal permeability of one to two orders of magnitude greater than the vertical permeability. The complexity in depositional characteristics in a tailings impoundment results in extremely complex variations in the local permeability values.

Frost has two major effects on permeability (SRK 1987). Frozen zones are effectively impermeable, blocking the passage of all water. Freeze-thaw cycles result in the formation of permeable flow channels and passages in the tailings. Thus tailings that have been subjected to freeze thaw cycles may become two or more orders of magnitude more permeable. The effect of frost on the long term yield of seepage from a uranium tailings impoundment is large. Contained ice, at closure, will considerably reduce the seepage rate but may prolong the period of contaminated seepage from the tailings. Frost



LONGITUDINAL SECTION



TRANSVERSE SECTION

Figure 6.2-5 Rabbit Lake - Settlement Profiles, Full Evaporation, Cover Constructed Immediately Following Tailings Deposition (after Geocon 1986)

induced increases in the permeability of thawed tailings would increase seepage and leaching rates. The full effects of frost action on tailings are not yet fully understood. Nevertheless frost action is considered to play a major role in the long term performance of tailings impoundments in discontinuous permafrost areas such as Northern Saskatchewan.

Some typical values of permeability for unfrozen Canadian tailings deposits are shown in Tables 3.3-1 and 3.3-2 in Chapter 3.

6.2.1.5 Strength and Trafficability

The shear strength of tailings is described by the equation:

$$s = c' + (\sigma - u)\tan \phi'$$

where, s is the shear strength of the tailings,
c' and ϕ' are the effective cohesion and friction angle of the tailings as defined in classical soil mechanics theory,
σ is the normal stress on the failure surface, and
u is the porewater pressure on the failure surface.

The effective cohesion is usually very small in the under or normally consolidated tailings. Thus the shear strength exhibited by tailings is mainly due to the effective friction angle, ϕ'. The term in which ϕ' appears includes the sum of the normal stress less the effective pore pressure. If the tailings are dry then u is zero and the tailings have an appreciable shear strength. Thus it is possible to travel on the dry beach areas of tailings impoundments. In the saturated areas, the application of a load causes pore pressures to rise resulting in low shear strengths. Thus it not possible to travel with construction equipment on wet tailings fines. Where tailings are very coarse, the rate of drainage and pore pressure dissipation is sufficiently fast to allow significant loads to be applied to the tailings. Thus it is possible to construct embankments on the coarse beach tailings even though they may be saturated.

During dynamic events, such as earthquakes, the tailings are subjected to rapid reversals of shear loads. Under these loads relatively low density tailings may consolidate, resulting in the generation of high pore pressures and a large loss in shear strength. Both the Elliot Lake and Saskatchewan uranium mining areas occur in regions of low seismicity and the risk of such strength reductions is small. Should uranium tailings impoundments be constructed in more active zones this form of strength loss may become a significant concern. Discussions and texts on appropriate evaluation and design methodologies are provided elsewhere (ASCE 1982, Vick 1983, and Vick et al 1985).

Typical effective shear strength parameters for Canadian tailings are provided on Tables 3.3-1 and 3.3-2 in Chapter 3.

6.2.1.6 Thermal Properties

Accumulation of frozen tailings can occur both during deposition in the tailings, as frozen layers of tailings are covered over by successive layers, and following discontinuation of tailings placement, as a result of the seasonal frost penetration. Should the seasonal depth of freezing exceed the seasonal depth of thawing, then frost may gradually form deeper into the tailings deposit resulting in permafrost conditions. The depth of frost penetration is dependant on a number of factors outlined in Chapter 8.4, including the thermal properties of the tailings. The major thermal property of the tailings is the thermal conductivity which determines the rate at which the frost front will advance into the tailings. This property is substantially dependent on the moisture content of the tailings. Since the moisture contents are generally greatest in the slimes areas of the tailings, these are also the most frost susceptible zones.

6.2.1.7 Chemical Properties

In general most of the minerals in uranium tailings are chemically stable, apart from traces of certain minerals that may go into solution and change properties in time. The major exceptions are sulphide minerals which oxidize and generate acid leachates, see Section 8.5, and gypsum which can dissolve and recrystallize as discussed in Sub-Section 6.2.1.1 above.

The chemical properties of the uranium tailings in the Elliot Lake area have been thoroughly studied by Golder Associates, CANMET and the University of Waterloo (Golder 1981, Cherry et al 1980, Dave et al 1981, 1982, Dubrovsky et al 1985 and Feenstra et al 1981). Similarly considerable data has been assembled on the chemical properties of Saskatchewan uranium tailings (Gulf Minerals 1981, Eldorado Resources 1984, MacLaren Engineers 1984, Amok 1985 and Knight and Piesold 1985.)

6.2.1.8 Physical Characterization of Tailings Deposits

The characteristics of uranium tailings deposits, just as for other tailings, vary according to grain size, density and the consolidation properties. To collect information on these properties in situ it is necessary to carry out field investigations of the deposits. Techniques used for these investigations are similar to those for investigating other soft saturated soils found in such areas as river deltas and marine environments. To assist in the development of investigation and sampling methods a manual has been prepared under the NUTP program entitled "Uranium Tailings Sampling Manual" by Golder Associates and Senes Consultants 1985.

Tailings solids samples are particularly difficult to retrieve without disturbing the tailings or their structural packing. To do so use must be made of specialized sampling equipment such as piston samplers or continuous samples such as the Delft continuous sampler as described by Follin et al 1984. Such samplers yield undisturbed samples for density measurements and for an examination of the detailed stratification and layering. Photo 6.2-1 shows a portion of a tailings profile obtained using a continuous sampler. The detailed layering is clearly apparent.

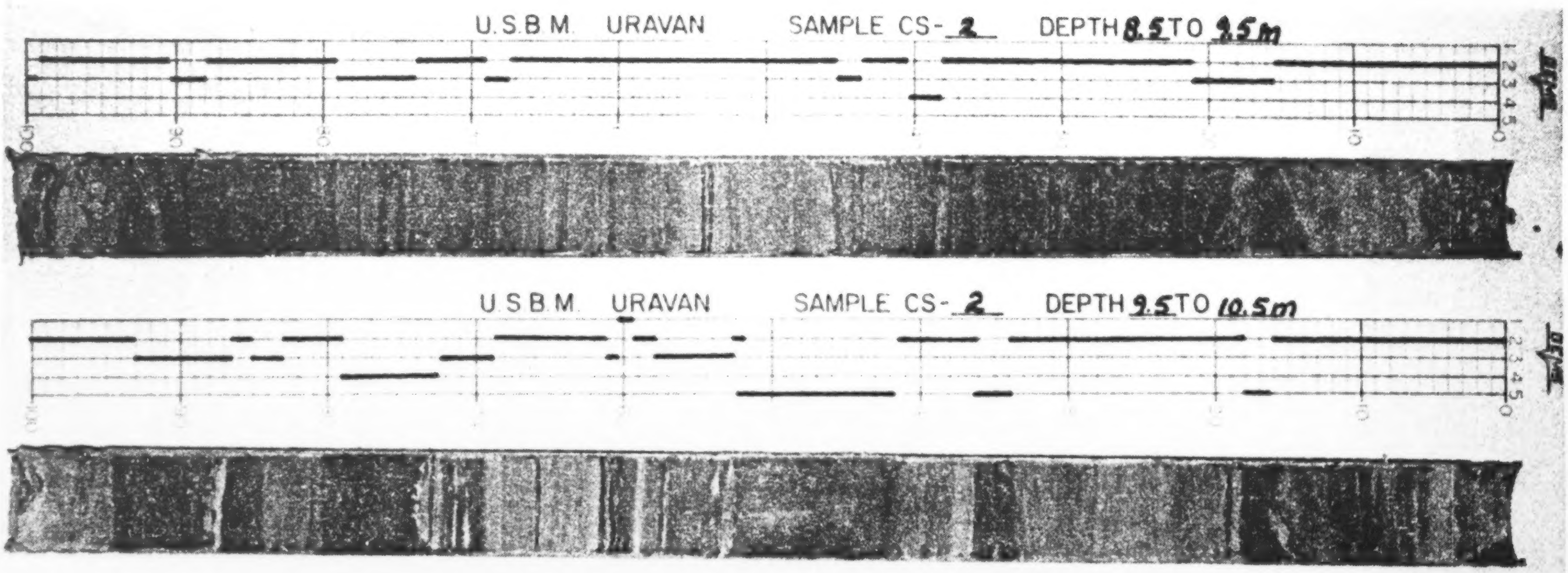
The piezocone (Rust et al 1984) penetration test has the advantage that it tests the tailings along a vertical profile in-situ and can provide details of the layering, its density and type, as well as a profile of the ambient pore pressure. Figure 6.2-6 is the record of a piezocone penetration test at Rabbit Lake (Geocon 1986) indicating a tailings impoundment with pore water pressure distribution which is at or above the hydrostatic value, with the water level at the tailings surface. Figure 6.2-7 is the record of a piezocone penetration test at Uravan tailings impoundment in Colorado where natural underdrainage has resulted in drawdown of the phreatic surface such that only a few low pressure perched water tables remain above low permeability slimes layers.

Where tailings may contain ice, use must be made of piezocones with temperature sensors, or drilling techniques which enable frozen samples to be recovered and preserved.

When performing laboratory testing, care must be exercised to ensure that both the sample and test conditions are representative of field conditions. Test methods are adequately described in standard texts in soil mechanics.

The detailed physical characterization of a tailings deposit, its zones of coarse and fine deposits, detailed layering, pore pressure distribution and location of frozen zones is necessary for a complete understanding of its physical behavior.

Photo 6.2-1 Continuous sample of tailings using a Delft sampler.


U.S.B.M. URAVAN SAMPLE CS-2 DEPTH 8.5 TO 9.5m
1 2 3 4 5
0
10
30
100
U.S.B.M. URAVAN SAMPLE CS-2 DEPTH 9.5 TO 10.5m
1 2 3 4 5
0
100

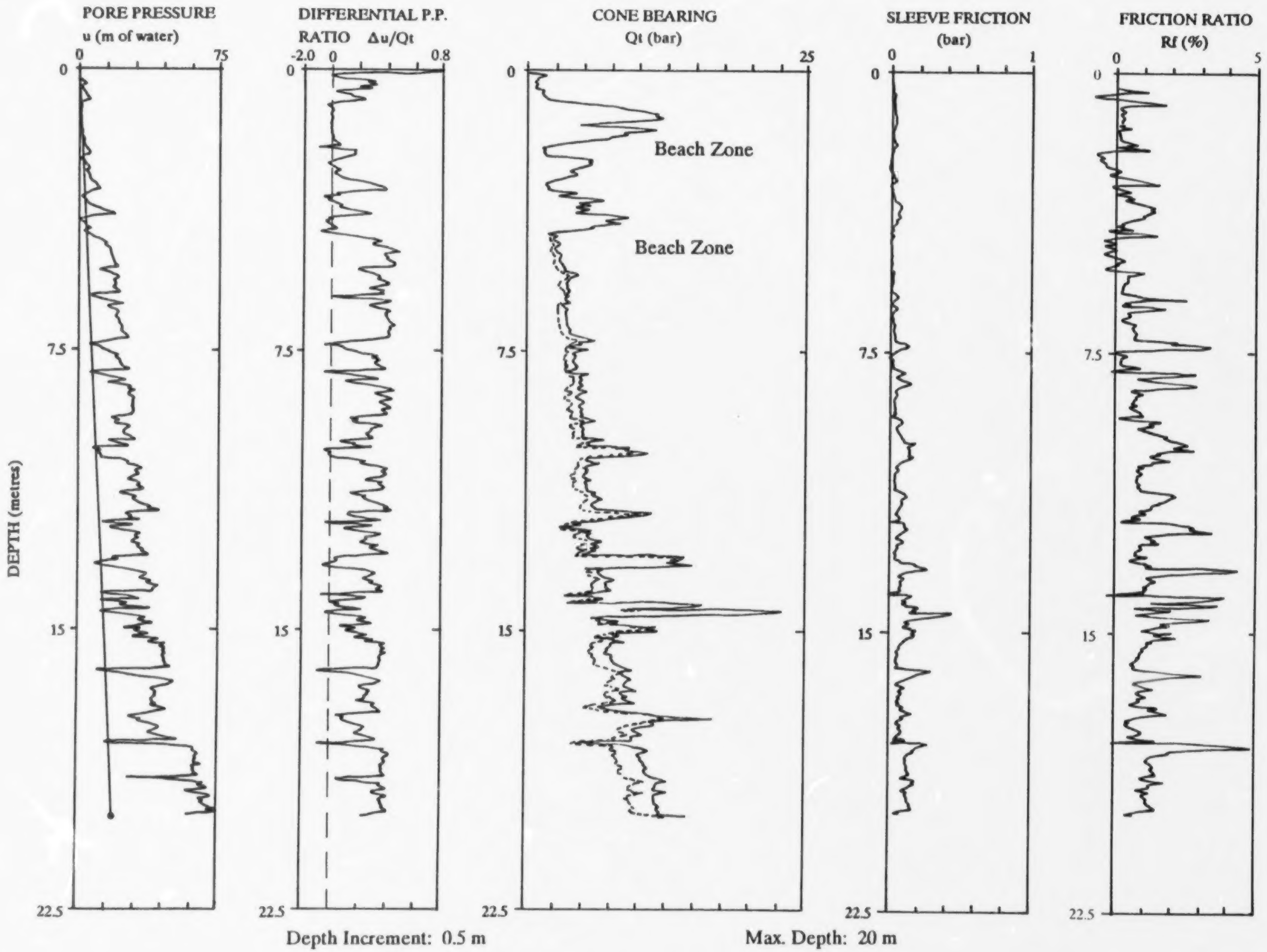


Figure 6.2-6 Piezocone Test at Rabbit Lake (after Geocon 1986)

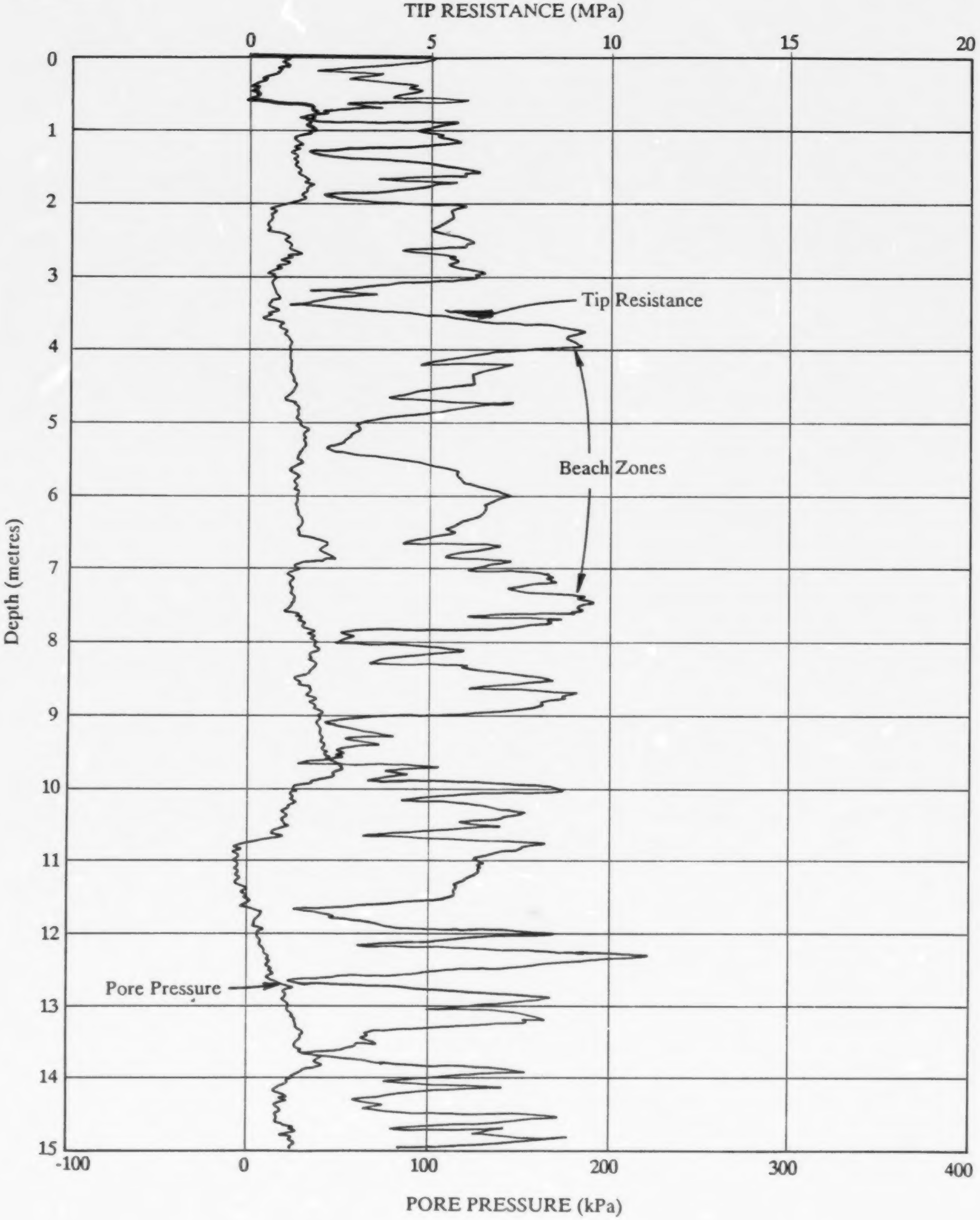


Figure 6.2-7 Uranium Tailings Profile Determined by a Piezocone Penetrometer (after Rust et al 1984)

6.2.2 DEWATERING TAILINGS

Tailings placement options are dependent on the slurry density or moisture content at which tailings are delivered to the tailings impoundment. In the last stages of uranium extraction the tailings are subjected to various degrees of washing and dewatering to minimize uranium losses in the solution which accompanies the tailings to the impoundments. The stages of leach pulp washing and thickening employed at the various Canadian mills are described in Chapter 3. These range from thickening using cyclones for the sands and CCD's for the slimes, as at Rio Algom Quirke, to drum fillers and repulping as at Denison, to a combination of CCD thickened tailings with disk filtered raffinate as at Rabbit Lake, Collins Bay B-Zone. Additional waste streams, such as raffinate from the solvent extraction circuit and excess barren solution from the ion exchange, are added to the tailings reducing the slurry density.

Tailings slurry with low clay, low gypsum contents, such as from Elliot Lake operations, may be discharged to the tailings impoundments at low slurry densities, since the solids separate out rapidly allowing the rapid decant and return of clarified water. For tailings with a high clay and gypsum content such as at Key Lake and the Collins Bay B-Zone tailings, settling is less rapid and sedimentation produces a lower density tailings deposit. Dewatering of such tailings, in the mill, to produce a higher density slurry has the advantage of improving consolidation of the tailings in the tailings impoundments, reducing the volume required for tailings containment and cover settlement after impoundment close-out.

In general, the finer and more clayey the tailings, the more difficult they are to dewater and thickened. Sands can be readily dewatered to 75% solids or greater by cyclones. Slimes are typically thickened to 30 to 60% solids in CCD thickeners. Vacuum disk, drum or belt filters, belt presses or filter presses may be able to reduce moisture contents to 20% or less for low clay ores. For raffinates, such as those filtered at Dong-Trieu, France (Robertson et al 1982) and Collins Bay D-Zone, vacuum filtration may result in filtrates with moisture contents of greater than 65%. With vacuum belt filtration of both the tailings and the raffinate at Dong-Trieu, a moisture content of 45% was achieved in the combined tailings. At Rabbit Lake, Collins Bay D-Zone the combination of CCD thickening of the tailings and vacuum disk filtering of the raffinate has resulted in moisture contents significantly greater. At these moisture contents the tailings are a sloppy semi-slurry requiring embankments for retention.

Once deposited in the impoundment the tailings will consolidate, resulting in an upward bleed of expelled water which will run down the beach to the pond from where it can be decanted. Decanting can be done by fixed penstocks or floating barge mounted pumps. The latter method permits a greater flexibility for pool location and is favoured in Northern Canada as it has a number of operational advantages in cold winter conditions. A novel form of decant is employed at Key Lake where pond water is decanted by allowing it to infiltrate into a sand blanket drain on the upstream face of the embankment from where it flows into a collector drain pipe in the base of the blanket drain.

Evaporative drying will result in the upward migration of additional water and further consolidation and dewatering of the tailings as described in Section 6.2.1. Promotion of such air drying is one of the objectives of the tailings deposit system installed at Key Lake.

Installation of underdrains, as at Key Lake, will increase the downward hydraulic gradient through the tailings deposit and considerably enhance dewatering. Dissipation of the pore pressures within the tailings, as a result of underdrainage, increases the effective stress in the tailings and accelerates consolidation.

The Saskatchewan generic Semi-Dry site uses construction and field dewatering techniques intended to maximize dewatering. These include:

- tailings thickening in the mill using CCD's,

- layered deposition to maximize sedimentation density,
- minimizing pool size to maximize beach area and evaporation, and
- underdrainage to enhance drainage.

All the field dewatering techniques are frustrated if the tailings are frozen or if the drainage path is blocked by frozen layers.

6.2.3 IMPOUNDMENT CONSTRUCTION METHODS

6.2.3.1 Construction with "Dry" Tailings

Methods of dewatering tailings and techniques for handling and placing have been discussed elsewhere (Robertson et al 1982).

The degree to which dewatering can be achieved depends on both the nature of the tailings and the equipment used. Tailings products may range from a sloppy semi-slurry to a product that behaves essentially as a dry granular material.

The handleability, trafficability and stability of the dewatered product is critically dependent on the degree of dewatering achieved. A sloppy, semi-slurry cannot be travelled on and requires embankments for its containment. It therefore requires specialized placement equipment such as conveyors, chutes or pipes. The "dry" tailings placed in the Collins Bay B-Zone in-pit impoundment behaves essentially as a slurry deposit and is placed by pipe. By co-disposing sloppy tailings and other dry mine wastes it is possible to achieve "near dry" pile conditions. At Dong-Trieu mine, the sloppy, tailings are trucked to ring dyke impoundments and mixed with rock waste in a co-disposal system to maintain trafficability. Near dry granular tailings can be handled by conventional earth moving equipment and placed in a conventional manner. Barton Mines, a garnet mine in New York State, have been operating a vacuum belt filter tailings dewatering scheme for coarse tailings which achieves a 14% moisture content and allows tailings pile development using a combination of conveyor and conventional earth moving equipment.

The only significant difference between a deposit of sloppy, dewatered tailings and a slurry placed tailings is the uniformity (lack of segregation) that results in the dewatered tailings deposit. Moisture contents at placement are so high that large consolidation settlements are required to expel excess pore water before consolidated densities and strengths are achieved. Thus the engineering properties of interest are essentially similar to those for tailings slurry deposits, except for the uniformity and isotropy of the deposit. Similar containment facilities are required, with similar seepage controls and abandonment measures.

Similar uniformity and isotropy can be achieved with a "near dry" tailings product. However, since the tailings are placed in a partially saturated state, they can be compacted to achieve high densities, and thus desirable consolidation or shear strength characteristics. Further consolidation and settlement can occur instantaneously under the placement of additional incumbent layers, and there is very little pile deformation after the end of construction. There is little restriction on the shape of pile that can be constructed. This allows the development of a tailings pile that is consolidated, stable and easily reclaimed at the end of construction. The long-term infiltration, leaching and seepage quality, however, are still concerns.

6.2.3.2 Construction with Slurry Tailings

Before reviewing how the engineering properties, of the deposited tailings, can be influenced by the depositional method it is appropriate to consider which tailings properties are most important in influencing construction methods and costs.

Three primary containment facilities are defined:

(i) No Embankment Facilities

Such facilities do not require the construction of an embankment. Examples are under sea or in-lake and in-pit disposal. The primary properties of interest for under water disposal are:

- angle of deposition slope and hence deposit geometry,
- liquid effluent quality and hence the impact on receiving waters,
- turbidity from discharges and flows, and
- susceptability to liquefaction.

An excellent text on marine disposal of tailings is provided in Ellis 1982.

For in-pit disposal the following properties are also of interest:

- average tailings density at closure and hence the mass capacity of the pit,
- consolidation following closure, hence cover deformation, and
- consolidation rates and permeability, hence leachate yields, operational and post closure leachate quality.

(ii) Central Discharge Facility

A central discharge cone deposit is illustrated in Figure 6.2-8 and is described by Robinsky 1975 and 1978. No embankments are required for tailings retention. The tailings property of most critical interest is the angle of the beach slope that will form since this determines the angle, location and volume of the cone. Tailings thickening is employed to increase the beach angles requiring an understanding of the relationship between the slurry density and beach angle. Additional parameters of interest are:

- the density of the tailings deposit for mass capacity determination,
- the relative density of the tailings below the saturated zone and hence its susceptability to liquefaction,
- erosion characteristics of the cone slope, and
- consolidation, permeability and leaching characteristics for long-term seepage qualities and rates.

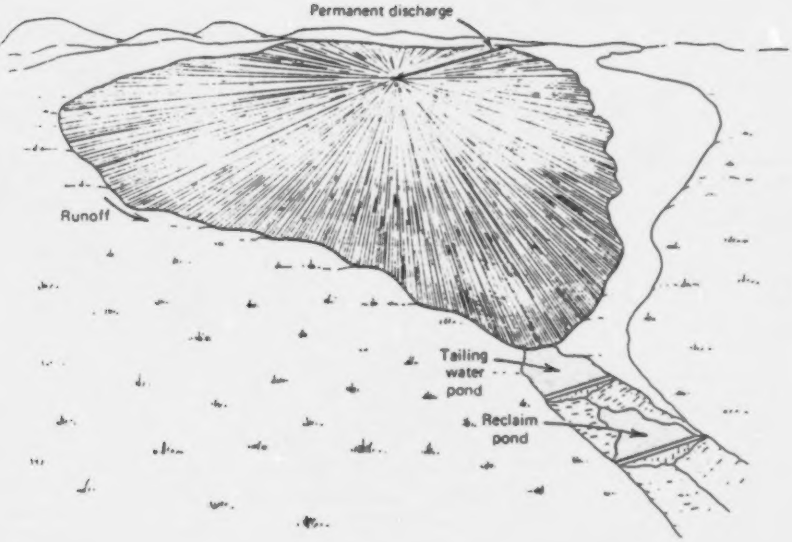


Figure 6.2-8 Thickened Tailing Central Discharge Method (after Robinsky 1979)

(iii) Embankment Retained Deposits

It is customary to divide tailings retention embankments into one of three classifications (ICOLD 1982). These methods of construction are illustrated in Figures 6.2-9, 10 and 11.

1. Upstream Construction

The impoundment crest is advanced upstream by periodically constructing small embankments on the tailings deposit immediately upstream from the previous embankment. The small embankments may be constructed of tailings and/or borrow materials, and are not usually critical in the overall embankment stability. The critical aspect is that the embankment is raised over previously deposited tailings and this requires that these underlying tailings have sufficient shear strength to be stable. Stability is achieved by one of two techniques.

(a) By constructing a graded beach deposit, as shown in Figure 6.2-9(a), by spigotting from the embankment such that the phreatic surface is drawn down low near the embankment so that it is consolidated (Blight 1987) and pore pressures are low.

(b) By constructing an outer zone in which the tailings have been compacted and drained by air drying. This system is referred to as either the paddock system or irrigation method as described by Gown and Williams 1987 and Gowan 1987 and is illustrated in Figures 6.2-9(b) and (c). Since the air drying is required to both dewater the tailings (preventing pore pressure generation) and to develop the negative pore pressures required to compact the tailings (Blight and Steffen 1979) the rate of rise is limited by the slurry setting density and local evaporative conditions. Maximum rates for Witwatersrand gold tailings and climatic conditions are provided by Wates et al 1987.

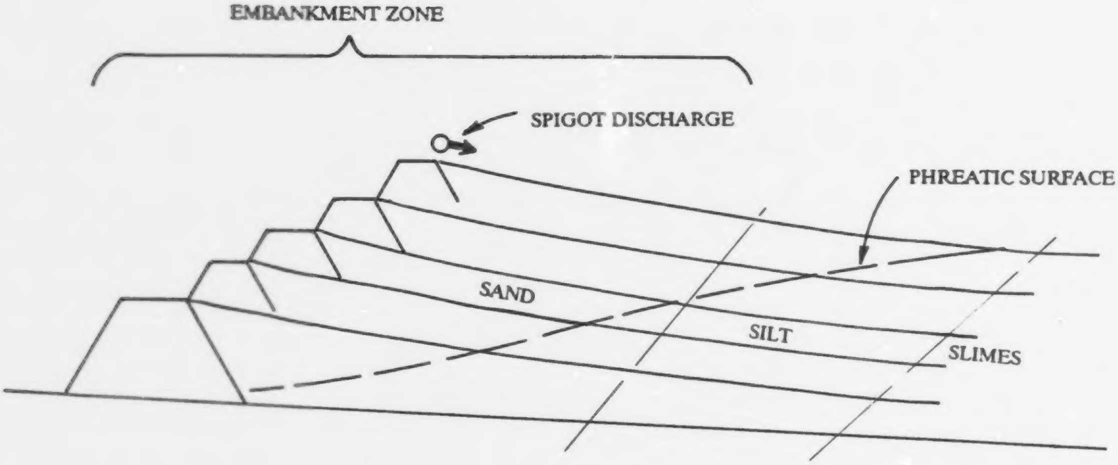

EMBANKMENT ZONE
SPIGOT DISCHARGE
PHREATIC SURFACE
SAND
SILT
SLIMES

Fig::re 6.2-9(a) Upstream Construction by Spigot Discharge

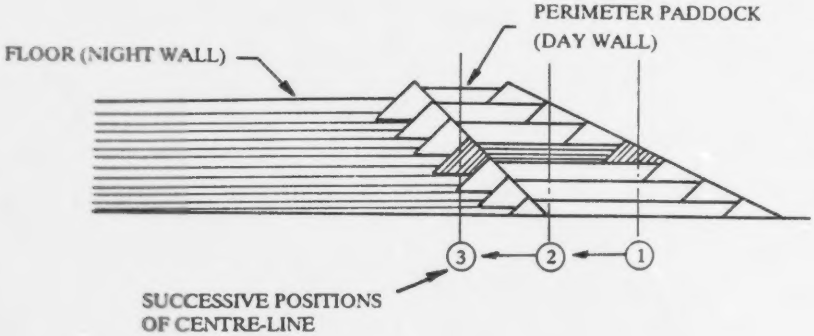

PERIMETER PADDOCK
(DAY WALL)
FLOOR (NIGHT WALL)
③
②
①
SUCCESSIVE POSITIONS
OF CENTRE-LINE

Figure 6.2-9(b) Paddock System: Upstream Construction

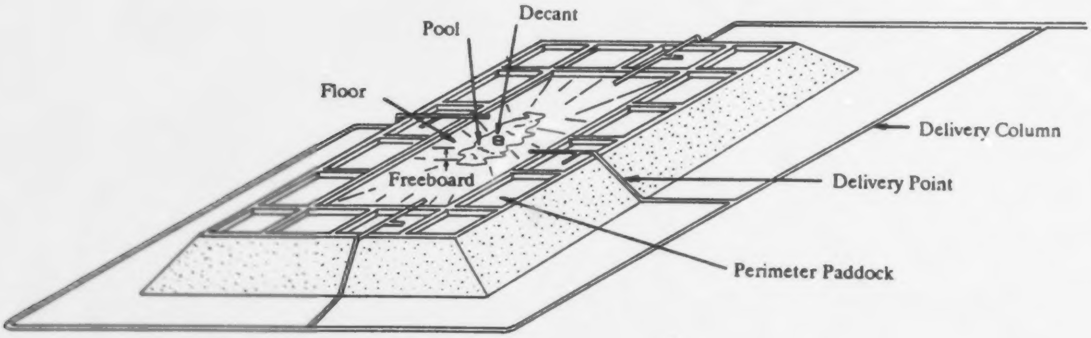

Decant
Pool
Floor
Freeboard
Delivery Column
Delivery Point
Perimeter Paddock

Figure 6.2-9(c) Paddock Deposition

The net evaporation applicable in most areas of Canada is considerably lower than the Witwatersrand area of South Africa and net precipitation occurs in many locations. During Canadian winters the net evaporation is effectively zero and evaporative consolidation does not occur. Application of this technique in those areas of Canada in which a net evaporation occurs may be feasible, but with a very low rates of rise and employing special procedures to allow for winter conditions.

Both the above methods usually include a system of underdrains under the embankment zones to assist in the drawdown of the phreatic surface.

Engineering properties of critical importance to these construction methods are:

- the segregation and hence grain size distribution along the beach and its variability, hence the increase in permeability from the pond to the embankment face,
- the density and compressibility of the tailings under the embankment crest which, together with the permeability (including effects of layering) and rate of embankment rise, determines the pore pressures developed under the embankment and hence its stability,
- ice lensing in the beaches (in winter) and its effects on drainage,
- the compressibility and consolidation of the soft slimes zone in the centre of the deposit and its effect on cap deformation and long term seepage releases, and
- permeability and leaching characteristics of the deposit and its effect on long term seepage quality.

2. Centreline Construction

With centreline construction the impoundment crest is raised vertically as the embankment is constructed, as illustrated in Figure 6.2-10. The embankment downstream from the centreline is constructed of materials over which some control can be exercised as to its permeability and compaction. Both borrow materials and cycloned tailings sands are often used. The individual lifts can be constructed in horizontal layers or layers parallel to the downstream slope of the embankment. An example of construction using compacted cycloned tailings sand is provided by Griffin et al 1983. Control of the downstream embankment properties permits stable conditions to be achieved in the embankment. The suitability and cost effectiveness of the method is dependent on there being sufficient coarse tailings to enable a sufficient split to be obtained. The degree of compaction and drainage required is dependent on the relative density achieved in the cycloned sands in the saturated zones.

Engineering properties of critical importance to this construction method are:

- the percentage of coarse tailings that can be spit for embankment construction,
- the relative density of the embankment sand and hence its susceptability to liquefaction,
- the potential for ice lensing and its effect on drainage in the embankment
- the consolidation and long term settlement of the slimes in the impoundments and its effect on reclamation covers and long term seepage, and
- the permeability and leaching characteristics of both the embankment sands and the fines and the resultant quantity and quality of long term seepage.

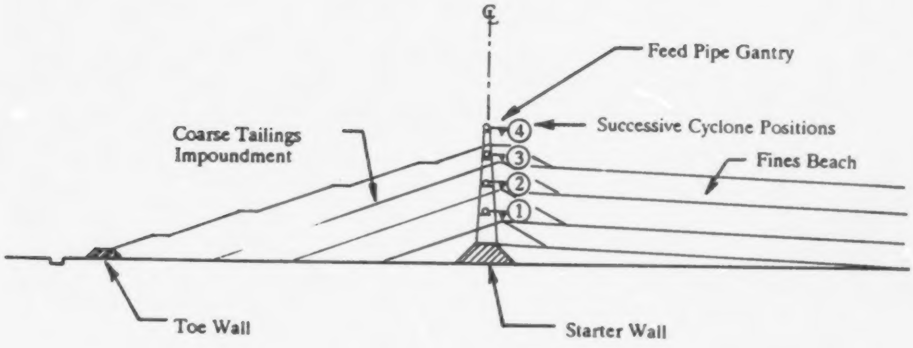

℄
Feed Pipe Gantry
Successive Cyclone Positions
Coarse Tailings Impoundment
Fines Beach
④
③
②
①
Toe Wall
Starter Wall

Figure 6.2-10 Cycloning by Centreline Method

3. Downstream Construction

Downstream construction is essentially a variation of centreline construction, in which the crest of the impoundment is advanced downstream as successive lifts are added, as illustrated in Figure 6.2-11. Such construction is normally used only where the tailings materials are extremely weak and provide little support to the upstream face of the embankment; where the water pool is impounded against the embankment; or where severe climatic, seismic or toxic tailings conditions warrant the additional security and costs. Because of public concerns regarding uranium tailings, use of this method is now generally favoured in Canada.

Engineering parameters of interest are essentially similar to those for centreline construction.

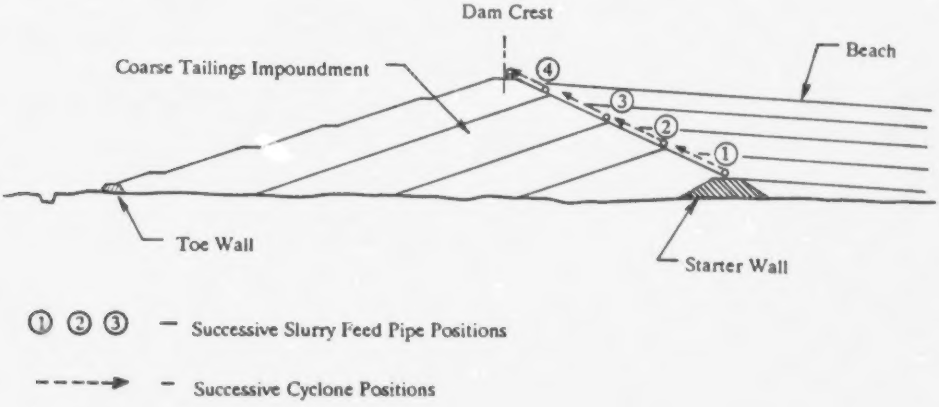

Dam Crest
Beach
Coarse Tailings Impoundment
④
③
②
①
Toe Wall
Starter Wall
① ② ③ – Successive Slurry Feed Pipe Positions
- - - - → – Successive Cyclone Positions

Figure 6.2-11 Cycloning by Downstream Method

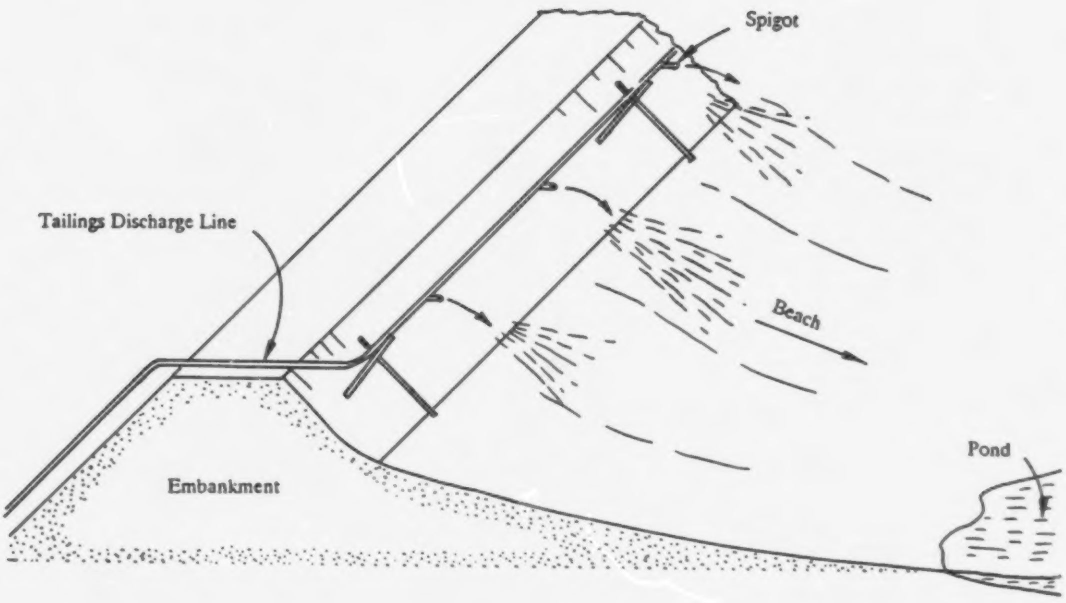


Figure 6.2-12 Tailings Deposition from Spigots

6.2.4 PLACEMENT AND SEDIMENTATION OF TAILINGS

6.2.4.1 Spigotted Tailings

Unclassified discharge of tailings takes place either by mass discharge from the end of the tailings pipe or by spigotting from a number of points on the upstream face of the tailings dam or around the impoundment. The tailings solids are deposited on the beach and fines and water flow out into the pool or pond, see Figure 6.2-12.

Engineering properties of tailings deposits placed as a slurry depend essentially on:

- degree of grain size classification and segregation that has occurred within the deposit,
- degree of consolidation the deposit has reached, and
- any cementing that may occur in the tailings.

The grain size classification that occurs along the beach of a tailings deposit has been examined by a number of researchers (Vic 1985, Melent'ev et al 1973, Blight 1987, Blight et al 1985, Wates et al 1987 and Williams and Morris 1987, Geocon 1986).

It has been shown that the profile of an hydraulic beach can be described by a dimensionless master beach profile, see Figure 6.2-13. This profile is the same for all beaches composed of a particular tailings material deposited at a specific solids concentration. The equation for the master beach profile, shown on Figure 6.2-13, contains an exponent, n, which characterizes each material and slurry solids content, but since the equation is dimensionless the parameter can be established from small-scale laboratory flume tests. The hydraulic sorting that occurs along the beach can also be predicted from a simple equation, thus enabling the permeability to be estimated, see Section 6.2.1.4. Since particle size and hence permeability decreases towards the pond, the phreatic surface in the embankment is lower than would be predicted assuming constant isotropic permeability.

It is apparent that different mechanisms cause the classification that is observed in tailings deposits. The first basic mechanism depends on slurry density. At very high slurry densities interference occurs (hindered settling). Coarse particles cannot settle out during flow, and this reduces the amount of classification and segregation along the flow path. Segregation tends to be prevented at solids to water ratios varying between 30 to 60% by weight depending on the grain size of the material; the lower solids content corresponds to clayey tailings such as at Key Lake, while the higher solids content corresponds to silty sand tailings such as at Elliot Lake. The second basic mechanism depends on the thickness of the flow. It is observed that if slurry of a given density is discharged as a shallow wide flow it tends to develop steeper beaches with less segregation than if it is discharged as a concentrated flow. Such wide shallow discharges, spreading out over the beach tend to have laminar flow, in contrast to the turbulent conditions developed in concentrated discharges.

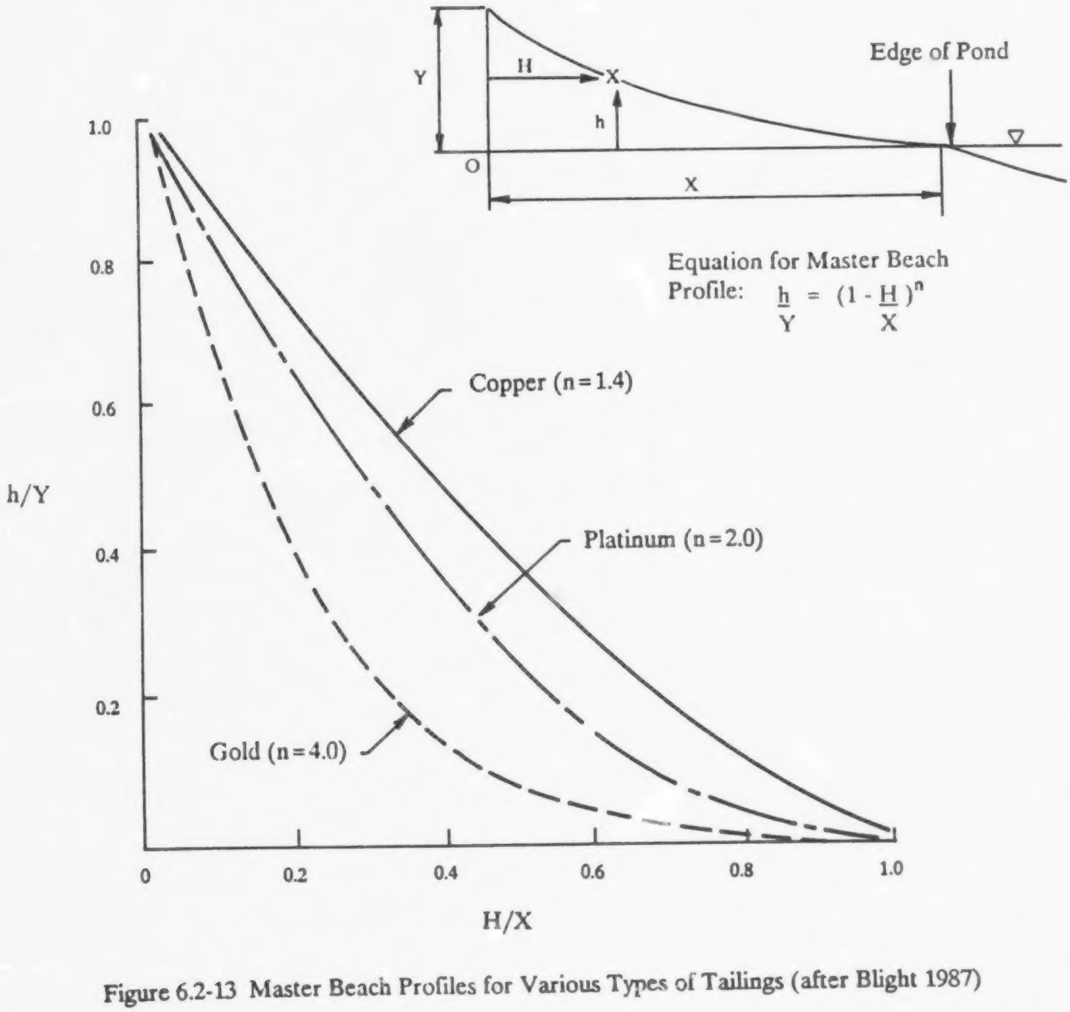


Figure 6.2-13 Master Beach Profiles for Various Types of Tailings (after Blight 1987)

Both mechanisms can be used to advantage to promote or restrict segregation along the beach. The least segregation is achieved by discharging thickened tailings through a system of spray bars with small, closely spaced spigots. This method is known as the sub-aerial technique, (Knight and Haile 1983, and Gowan and Williamson 1987), see Photo 6.2-2. The largest segregation results from the use of a single spigot discharge point and a low slurry density. Thus considerable segregation is anticipated during the initial deposition from any central discharge system (Robinsky 1975).

For low density slurry deposits, the tailings beach angle may be calculated from the master profile concept as described by Blight 1987, and the grain size distribution along the beach by the relationship proposed by Blight 1987 or Williams and Morris 1987. Beach angle determination for thickened uranium tailings may require field trials. A typical beach angle versus slurry density relationship is illustrated in Figure 6.2-14 (after Robinsky 1978).

In practice, many tailings beaches demonstrate a mixture of flow and depositional modes resulting from variations in slurry densities and the flow patterns that develop. These variations result in anisotropic deposits of coarse and fine grained layers. This non-uniform layering is important in determining the global engineering parameters, particularly the permeability and anisotropy within the beach deposits. The extent of such anisotropy and layering in any vertical profile in a typical spigotted beach deposit is seen in the piezocone profiles shown on Figures 6.2-6 and 7. The former figure is from the spigotted Rabbit Lake tailings deposit and is typical of any such deposit including the generic Saskatchewan Wet Site and the two Ontario Sites. In addition to this vertical segregation there is a lateral variation as has been simplified and idealized in the distribution shown in Figure 6.2-5.

Essentially the same sedimentation controls apply to sub-aqueous deposition, although the forces inducing flow are reduced by the smaller difference in density between slurry and water. Where

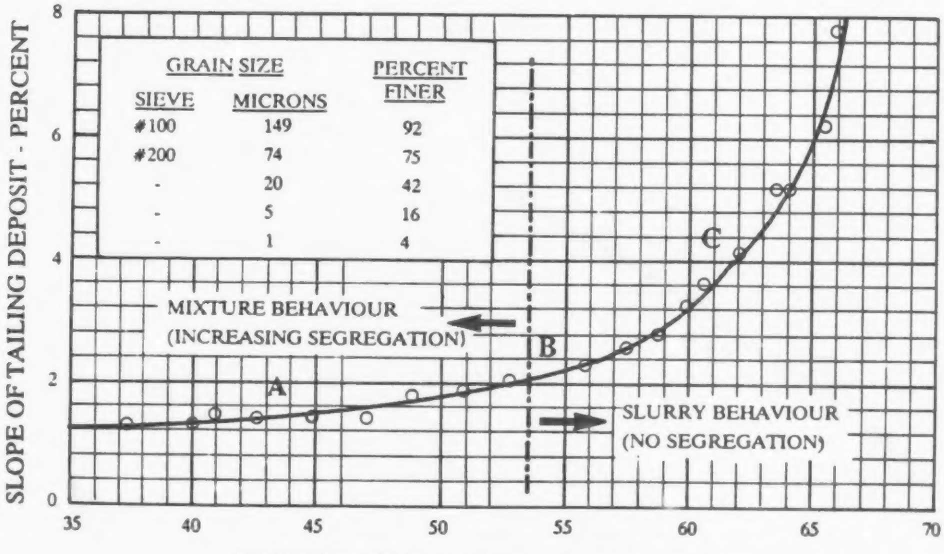


Figure 6.2-14 Laboratory Tailing Deposition Test Results. Magma Copper Company, Superior Division

concentrated discharges are made under water, the slurry flows as a density stream at shallow angles (a few degrees) for long distances, with segregation along the flow path. Where a shallow distributed flow enters a tailings pond, material is deposited rapidly with little segregation producing much steeper slopes.

6.2.4.2 Cycloned Tailings

Where there is a sufficient portion of the tailings with an average grain size in the sand classification (plus 200 mesh) to enable it to be split out and used as a construction material, consideration may be given to cyclone classification. The cyclone splits the tailings into a coarse, or sand fraction which is discharged at fairly low moisture content through the underflow and a fine, or slimes fraction at high moisture content through the overflow. The relatively free drainage characteristics of the sand fraction makes it suitable for embankment construction, when placed in slurry form. The underflow is used to construct the embankment while the overflow is retained behind the embankment as illustrated in Figure 6.2-15. Underdrains may be required to assist in the collection and removal of drainage and seepage waters from below the embankment.

Methods of cycloning and placement, and constraints on construction are detailed elsewhere (ICOLD 1982 and Vick 1983). In view of its limited potential for embankment construction for uranium tailings in Canada, discussion of this method is brief.

The sand fraction in the embankment is relatively isotropic, and permeable. It consolidates rapidly and allows a low water table to be maintained within the embankment. If placed without compaction it may achieve relative densities susceptable to liquefaction under seismic loadings. As a result of its high permeability there will be high seepage rates from the embankment underdrains in the long term. The permeable embankment is unsuitable for impounding water and it is therefore not feasible to flood the entire tailings surface for acid generation control purposes.

The slimes fraction behind the tailings embankment is placed by conventional spigotting techniques at a low slurry density. The properties of these fine-grained slurries are as discussed for spigotted layered slurried tailings.

6.2.5 THE EFFECTS OF PLACEMENT METHODS ON ENGINEERING PROPERTIES

a) Sub-Aqueous Discharge Deposits

Since deposition is below water, consolidation is due to the effective weight of incumbent layers only, resulting in very low density, under or normally consolidated deposits, particularly near the upper surface of the tailings. Such deposits are typical of the pond area of many tailings impoundments, which also represents a concentration of the finest grained portion of the tailings. Such deposits are characterized by a high void ratio, high compressibility and low permeability.

Following decommissioning, if there is a drawdown of the water table and air drying, such deposits are subject to large consolidations and settlements. Because of the water cover they are normally ice free. Estimates of the consolidation settlement for a typical deposit of this type indicate values approaching 20 to 30% of the deposit thickness (Geocon 1986).

If the water cover is maintained large additional consolidation settlements will not occur; oxygen entry and oxidation (acid generation) is prevented, but long-term seepage and embankment stability are important considerations.

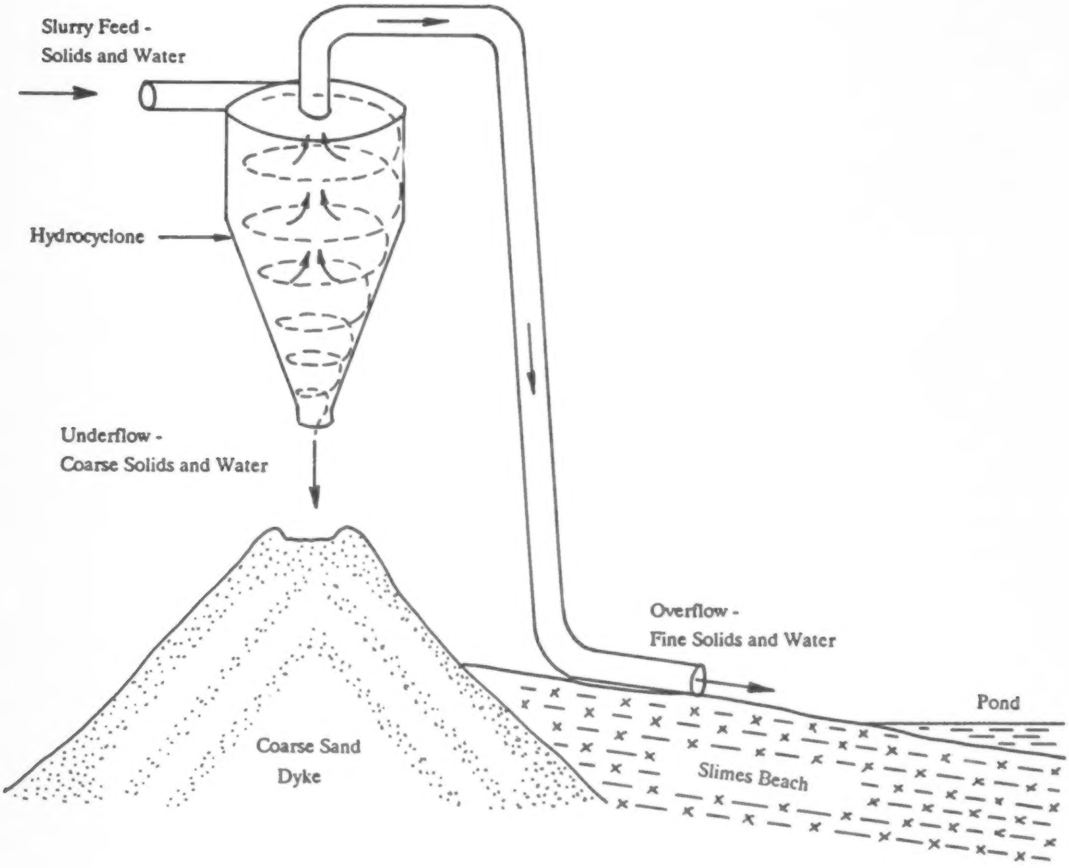

Slurry Feed -
Solids and Water
Hydrocyclone
Underflow -
Coarse Solids and Water
Overflow -
Fine Solids and Water
Pond
Coarse Sand
Dyke
Slimes Beach

Figure 6.2-15 Tailings Deposition by Cyclone Separation

b) Paddock System Deposits

The paddock system is not used anywhere in Canada in its true form as employed in South Africa (Figure 6.2-9(c))

In the embankment zone (day wall) of the paddock system, the thin, layered nature of the deposit results in a material with a fairly uniform distribution of grain sizes, although the engineering properties are anisotropic due to the layering. Partially saturated tailings conditions can be achieved, provided that the rate of rise during construction is low, evaporation is sufficiently high and resaturation is prevented by a suitable underdrainage system. If adequate dessication is achieved in the deposit, it is partially saturated or "semi-dry". Desiccation compaction results in relatively high densities compared with incumbent load consolidation only. Little or no additional settlement is anticipated after impoundment abandonment. Underdrainage must be maintained for embankment stability, and this may be a cause for concern for long-term seepage control. Since such impoundments, are not designed to store water over their entire surface it is not usually feasible to develop a water cover for acid generation control, and the partially saturated conditions of the deposit favour acid generation.

The engineering properties of the interior (night wall) zone is essentially similar to that for spigotted discharge deposits discussed below.

Paddock construction cannot be used during sustained freezing conditions. Rio Algom, Quirke uses a system of very large paddocks but they are operated as independent unthickened layered tailings impoundments.

c) Spigot Discharge Deposits

The character of the tailings deposit depends partly on whether or not the tailings are thickened prior to discharge.

(i) Thickened Layered Tailings Deposits

Thickened tailings, discharged through closely spaced spigots in thin layers, result in a deposit in which segregation is minimized. Such a discharge system is used at Key Lake as illustrated in Photos 6.2-2, 3 and 4. If upstream construction is employed then, since segregation is minimized, it is usually necessary to install an extensive underdrainage system to assist drainage and dewatering. Rates of rise must be kept low enough that either drainage or air drying will be sufficient to achieve pore pressure dissipation, thus ensuring embankment stability. If the tailings are placed in thin layers with a slow rate of rise, and if evaporation is sufficient to achieve dessication compaction and partly saturated conditions then the resulting deposit is "semi-dry". At Key Lake the embankments have been constructed of sand borrow material in a manner typical of the Saskatchewan generic semi-dry site. Thus reliance is not placed on air drying of the tailings to achieve embankment stability. In this instance thickened layered tailings techniques with underdrainage are employed in order to maximize the evaporative drying and draining of the main tailings deposit, hence achieve the maximum tailings density and minimum vertical permeability.

Should upstream construction methods be adopted embankment zones must of necessity be drained and consolidated. For finer grained tailings consolidation may depend on desiccation compaction and thus on the rate of rise. In wet and cold climatic conditions, desiccation compaction may be seasonally poor. Permeability is usually highly anisotropic and may be an order of magnitude or more greater parallel to the layering than normal to it. This may be further complicated by ice inclusion in the beach areas resulting from the depositional method during severe winter conditions. This leads to poor drainage towards the perimeter and underdrains and may result in perched water tables. Permeability is reduced in the partially saturated zones by both desiccation compaction and the blockage of flow in

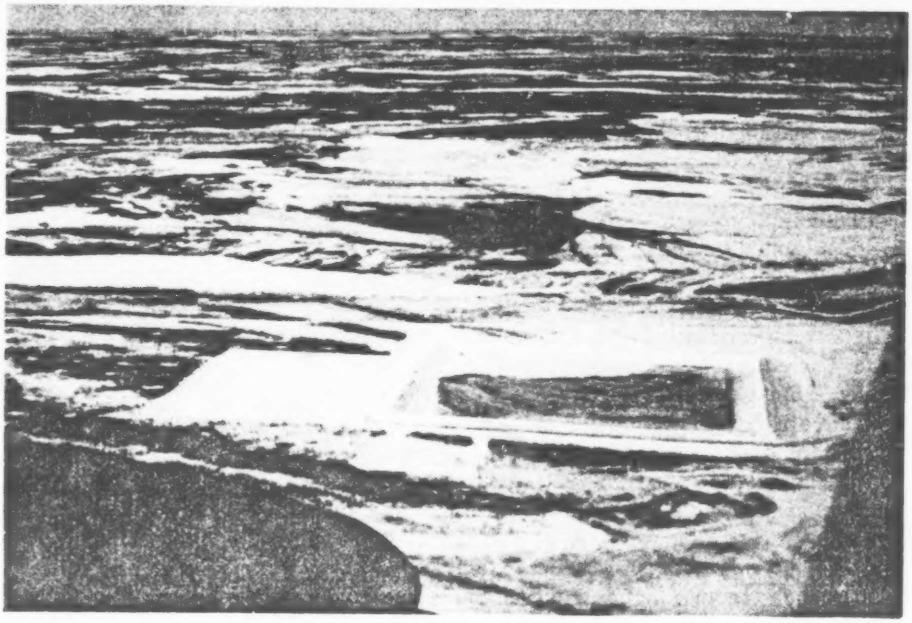


Photo 6.2-2 Sub-aerial tailings disposal, Key Lake, Saskatchewan.

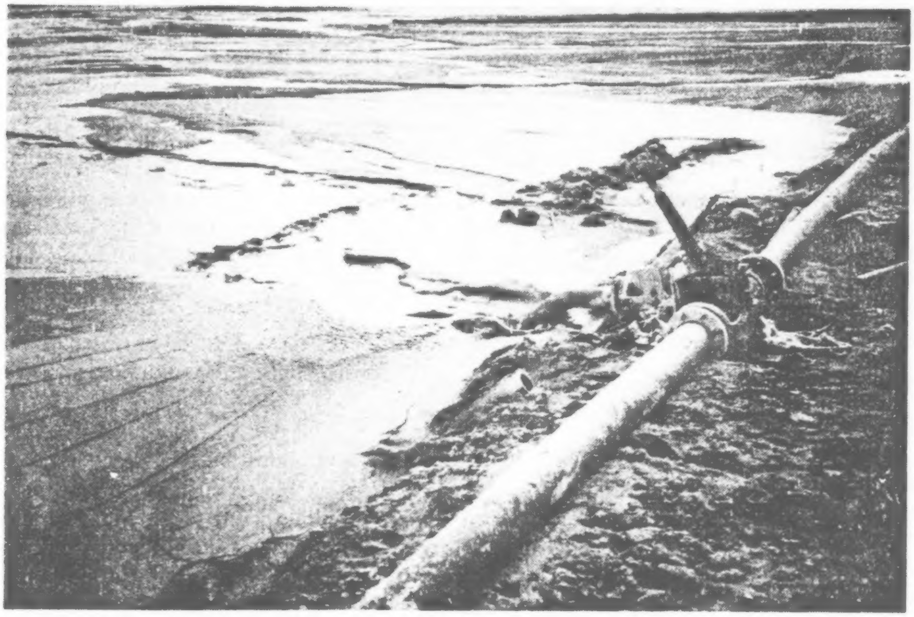


Photo 6.2-3 Spigotted discharge at Key Lake. Tailings are thickened to 40% solids prior to deposition.

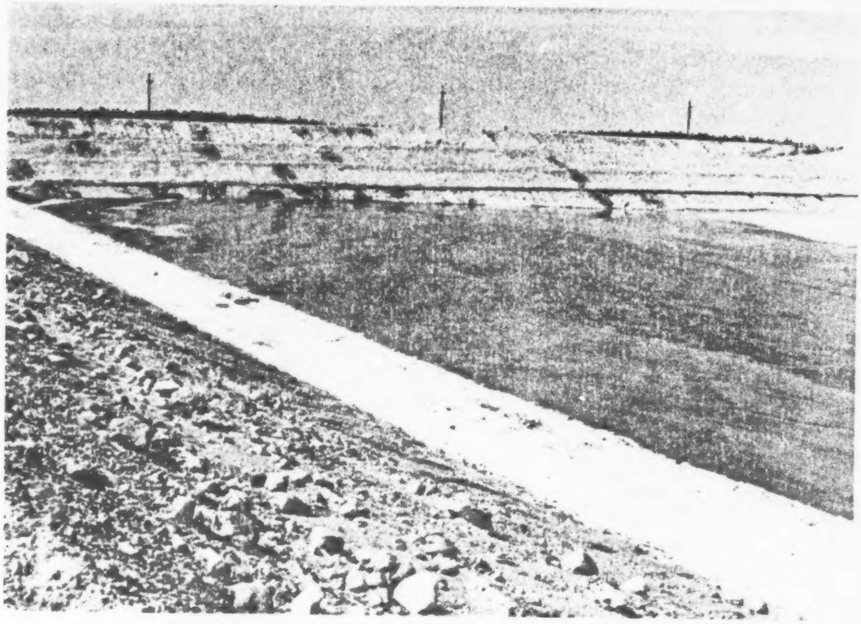


Photo 6.2-4 Layered tailings deposition at Key Lake.

the voids by air bubbles. Density is not increased, and permeability is not reduced in the zones where desiccation has not occurred (in the pool zone, in frozen zones or if wet climatic conditions prevent significant evaporation). Permeability is increased in any layers subject to freeze/thaw and is zero in any frozen tailings zones. Saturated zones of low density tailings may be susceptible to liquefaction during seismic events.

Large consolidation settlements are anticipated in the pond area and over beaches if frozen zones, developed during placement, subsequently thaw.

Drainage of any embankment zones constructed by upstream methods must be maintained in the long-term. This may be difficult to achieve, after abandonment, if seepage cannot be discharged. Control of acid generation by a water cover is not usually feasible, and the partially saturated state of the deposit favours acid generation.

At Key Lake, the thickened layered tailings system has not been operational for a sufficient period to obtain a clear definition of the tailings properties that will be achieved. Test work done to date (Knight and Piesold 1986) indicates significant layering. Vertical drainage to the underdrains appears to be much greater than anticipated, due probably to freeze thaw cracking. Freeze thaw also appears to be causing compaction of layers within the tailings, possibly to a greater extent than evaporative drying. The extent of ice lense development was not known at the time of writing this report.

(ii) Unthickened Layered Tailings Deposits

This form of placement technique has been used for placement in the impoundments at the generic Saskatchewan Wet Site and the Ontario Sites. This method is not being used for embankment construction at any of the currently operating uranium mill tailings impoundments in Canada, although it has been used at some of the abandoned properties.

Unthickened (low slurry density) tailings, placed through spigots onto wide beaches, will result in segregation along the beaches. The uniformity of segregation will depend largely on the uniformity of the placement conditions. Variations in the density of the slurry or discharge method, will result in variations in the grain size layering. Development of a coarse, drained outer zones to serve as embankments depends on having a well-graded tailings with a substantial coarse fraction (plus 200 mesh) and uniform placement conditions.

Grain size and permeability distribution estimates can be made as discussed in Section 6.2.4.1 (Blight 1987). Where upstream construction methods are used perimeter underdrainage is required to ensure drainage and consolidation of the embankment zones. Permeability will be anisotropic depending on the variations in tailings discharge conditions. Beach deposition is conducive to ice development, and included ice lensing would considerably increase the degree of anisotropy of permeability. The resultant anisotropy of the tailings properties have been clearly demonstrated in the investigation and characterization work done on the Rabbit Lake tailings impoundment as described by Geocon 1986.

Some desiccation consolidation may occur but this does not normally contribute significantly to densification. Embankment zones are expected to be normally consolidated when drained. The low density embankment sands are susceptible to liquefaction if saturated. Some zones with saturated perched water tables can be anticipated. The interior of the impoundment can be under or normally consolidated, beneath a high water table. The pond zone will be fine grained material, ice free with a high void ratio.

Following abandonment, if the water table drops as a result of drainage, surface desiccation occurs, entrapped ice melts and large surface settlements can occur. Lowering of the water table is the single most important natural process controlling the settlement of a tailings deposit on abandonment (Geocon 1986). Seepage from the more permeable embankment zones can be anticipated for a long time following closure as consolidation of the impoundment interior progresses. Where upstream construction has been used for the embankments a complete water cover is not feasible.

d) Central Discharge Cones

Placement of thickened tailings using a central discharge to form a cone-shaped deposit is essentially a variation of the spigot discharge technique. This form of deposition is being applied for a modified geometry in the in-pit disposal at Rabbit Lake, Collins Bay B-Zone. For the traditional cone deposits the same range of engineering properties and concerns exist as for spigotted deposits. Some primary differences in behaviour of the deposits are:

- there is no need to maintain an underdrainage system to ensure embankment stability,
- post-closure settlement patterns are such that drainage patterns will be preserved,
- susceptibility to liquefaction is reduced because of the low slope angle, and
- erosion of the tailings surface in the long-term is a greater concern.

Drawbacks of the method are that the ability to achieve highly-thickened tailings is often not feasible for economic reasons; frost penetration on the exposed slopes; and the necessity for perpetual treatment of long term drainage from the deposit.

For the Collins Bay B-Zone in-pit deposit, considerable difficulty has been experienced in achieving consistent thickened tailings and in the development of an economic method for their placement. Long term consolidation and leachate drainage from underconsolidated and frozen tailings will determine long term seepage quality and surface consolidation.

6.2.6 IMPROVEMENT OF DRAINAGE AND CONSOLIDATION

Uranium tailings sands in general have good consolidation characteristics. Tailings slimes and high clay/gypsum tailings consolidate much more slowly. High gypsum tailings are expected to exhibit long term secondary consolidation (Wrench and Blight 1985). While it has been found by a number of recent workers (Geocon 1986) that the rates of consolidation of loosely deposited sediments are in general much higher than earlier theoretical analyses had predicted, settlement periods of 20 or more years are anticipated in the slime zones.

During the settlement period surface caps and covers are distorted, drainage patterns are disturbed and seepage must be treated. Accelerated dewatering and drainage would have the advantage of allowing early implementation of close-out measures.

6.2.6.1 Drainage in New Tailings Deposits

Various enhanced drainage techniques, utilizing consolidation under self-weight of the tailings during deposition, have been reviewed for the NUTP (Geocon 1986). These include interior drainage utilizing tailings segregation. This often occurs naturally as with the Elliot Lake and Rabbit Lake tailings unless particularly measures have been taken to minimize segregation. Collector drains can be laid at the base of the deposit and protected by filters; seepage being fed by a blanket drain beneath the entire deposit (Charlie and Martin 1980). The blanket underdrain installed at Key Lake (Knight and Piesold 1986) is very effective in enabling rapid dissipation of pore pressures and settlement of the hydraulically placed tailings. Alternatively the blanket drain can be replaced by simple finger drains (Lubina, Hovater and McCready 1980).

The installation of underdrainage results in an increase in the hydraulic gradient through the tailings. This could result in increased seepage and leaching after close-out. Provision for the discharge of such long term seepage from the underdrains must be provided for.

The sub-aerial technique (thickened layered tailings) can also be used to enhance evaporative drainage as at the Key Lake impoundment.

6.2.6.2 Drainage and Promotion of Consolidation at Existing Deposits

Promotion of post-depositional tailings consolidation has two objectives:

- minimization of settlement beneath the cover after placement, and
- ease of access over the tailings surface during cover construction.

Cover construction can be planned to take advantage of desiccation effects in the most compressible upper part of the tailings. By deferring cover construction for some period of time depending upon the particular deposit, a large part of the post-depositional settlement, which would otherwise affect the cover, can be avoided. The time for desiccation and consolidation of slimes can be estimated by methods developed for dredged materials (Krizek et al 1975 and 1977). Settlement can be further induced by applying a surcharge fill. Details of deferred cover construction and the use of surcharge, together with gravity drainage and pumping of clarification ponds have been reviewed for NUTP by Geocon 1986.

Other methods of promoting consolidation with possible application to tailings are:

- deep wells,
- well-points,

- sand drains and wicks, and
- electro-osmosis.

All these methods are costly. The effectiveness of deep wells and well-points is limited, since the cone of depression around the well is narrow in tailings. As a result large numbers of wells at close spacings are needed. Sand drains and wicks tend to be clogged by slimes, while electro-osmosis, which is applied to a special well-point system to accelerate drainage, is very expensive. Detailed descriptions of these techniques and comparative costs have been reported for application in uranium tailings in the USA (Wardell et al 1983).

CHAPTER 7.0
CONTROL STRUCTURES

Since a thorough treatment of many aspects of control structures for tailings impoundments appear in the chapter of waste embankments in the Pit Slope Manual (CANMET 1977), only those aspects that are peculiar to uranium tailings impoundments will be discussed in more detail herein. The summary from the Pit Slope Manual is reproduced in Appendix A.

Barriers to seepage and radon are a particular feature of uranium tailings impoundment and these are discussed, together with technology for wastewater and other wastes.

7.1 EMBANKMENT DAMS AND DYKES

7.1.1 GENERAL

Although the volume and the cost of earthworks for covers and liners may exceed the requirement for embankments, the latter is the principal engineering control structure confining the tailings. The embankment has to be designed to retain water as well as solids. The action of water, either through pore pressures or by piping erosion, is the main agent causing instability in embankments.

Careful site investigation, design and construction control are needed to engineer sound tailings impoundments. This work should be by an engineer or engineers with a good practical and theoretical understanding of geotechnics, hydrology, geohydrology and geochemistry. The responsibilities for design and construction must not be divorced so that the designer does not know what the contractor or operator is doing, nor the latter realize what the designer intended. Such a division of responsibility has led to an embarrassingly high number of failures of earthworks. Failures have occurred largely due to the irregular patterns of deposition of geological materials in foundation strata, and improper placement and compaction procedures for earthfills.

It is therefore usual to design tailings embankments according to conventional water supply dam design principles using either homogeneous, low permeability materials in thin well-compacted lifts, or internal zoning with a variety of materials but including some low permeability core material. Zoned embankments usually require internal filter zones to prevent migration of fine materials into the void spaces between coarse particles in outer zones. Both the embankment and the basin sides and floor should provide contaminant by virtue of their low permeability. This may require the use of a low permeability liner integral with the core of the embankment. Obviously if a basin of natural low permeability exists this is a great asset.

7.1.2 METHODS OF CONSTRUCTION

While tailings embankment may be constructed using a portion of the tailings in the interior zones of impoundments, it is generally considered inadvisable to use tailings for above ground construction. Instead embankments should be constructed of selected, non-radioactive, inert (i.e., non-pyritic) borrow materials or waste rock from mine pit excavations.

The three methods of embankment construction used for tailings impoundments are the upstream, downstream and centreline method, each having merits and demerits (CANMET 1977). The soundest method of construction is the downstream technique. It is used when tailings are fine grained or toxic, or where the environment is wet, seismic or sensitive, (Caldwell and Smith 1985) for further details and a recent review of design details, including a discussion of hydrogeochemical considerations.

Compaction is the major technique used to ensure strength and low permeability in embankment fill materials. This require the use of appropriate equipment and fairly stringent control of material lift thicknesses and moisture contents.

To minimize costs suitable borrow materials should be sought with the minimum haul distance to the embankment. Often materials can be found from within the tailings impoundment. The space excavated then become additional tailing storage volume.

Embankment should always be designed with a view to ease of construction. For example vertical dam cores are easier to build than sloping cores. Intricate filter designs often wear down the patience of the contractor. If they appear necessary, alternative materials should be selected for the incompatible zones, and simple, easy to construct, filters provided. Dams are designed by appropriate selection of materials and configurations based on experience and judgement. They are not designed on the basis of, nor as an outcome of, stability computations, as might be believed by a perusal of some reports. Stability analyses are performed on dam designs conceived *a priori*. They are a check only, and undue reliance should not be placed on computed factors of safety. Many slopes with a computed factor of safety exceeding unity have failed, much to the surprise of the analyst. For the comments of a well-recognized dam expert on failure conditions see Section 7.1.4. Embankment foundations are critical components of the structure, needing careful assessment for shear strength, compressibility and permeability characteristics. Excavation and replacement of unsuitable materials in foundation strata is often preferable, and sometime vital to ensure embankment integrity.

During the investigation stage for an impoundment an eye should be kept open for "treacherous soils". In Canada these tend to be:

a) soft sensitive clay deposits, either of marine or glacial lake origin,
b) very loose layers of fine sands and silts, and
c) hard clays or clay shales, containing thin seams of bentonite that are often difficult to detect.

The treacherous nature of these deposits resides in the fact that they can precipitate catastrophic failures with little warning. Such materials lose most of their strength after initial peak shear strengths are exceeded, resulting in the development of a flow slide travelling considerable distances.

Spigotted tailings very often fall into category (b) above, and for this reason the use of fine tailings is discouraged for embankment materials, particularly using the upstream method of staged construction. If tailings sands have to be used the downstream method, or at the very least the centreline method should be specified. This recommendation is made regardless of seismic risk, to which the upstream method is known to be sensitive.

The obvious but often overlooked fact is that coarse grained materials are inherently more stable than fine grained soils. In general as embankment materials they are easier to place and compact during construction.

Some form of seepage barrier, see Section 7.3, is normally employed. This is usually the core of the dam in conjunction with a cutoff trench and a curtain of cement grouting in the rock foundations. Grouting however seldom does more than minimize seepage, (Casagrande 1961).

7.1.3 EMBANKMENT STABILITY

Because of the need for long-term control (SRK 1986) examined possible modes of physical instability in three embankments resulting from changes in:

- slope geometry,
- material properties,
- phreatic surfaces, and
- earthquake loadings.

Slope geometry could change as a result of surface flood or gully erosion, subsurface seepage erosion and freeze-thaw sloughing and slumping.

Changes in material properties can arise as a result of weathering action on the surface, or internal physical chemical or biological processes such as slaking of particle point contact in rockfills or change in clay mineralogy as result of leaching by groundwater.

A rise in the phreatic surface in an embankment can bring about failure and this can, for example, be caused by blockage of an underdrain, following precipitation of salt or by material sloughing over the exit or plant growth. Insufficient work has been done to define with certainty the potential for drain blockage that could occur at specific Canadian uranium tailings sites. For this reason designers should not place undue reliance on underdrainage for long-term stability.

Dynamic loadings cause horizontal thrusts that tend to shake embankments apart, but the worst threat is the resulting liquefaction that can occur in loose, saturated, fine grained sands or silts. Liquefaction can be partial or complete with dramatic consequence that would very probably result in a large release of tailings. Fairly reliable methods of analysis of liquefaction potential are available now, but the problem is best avoided if possible by selecting non-liquefiable construction materials and selection of sites where such soils are not encountered in the foundations. Glacial tills, compact sands and gravels, and rockfills are not susceptible to liquefaction.

Remedial measures for improving the stability of existing embankments are detailed in (CANMET 1977) include slope flattening, addition of berms, off-loading the embankment crest and the use of inverted loaded filters.

Seepage erosion of uranium tailings embankments can occur as a result of upward flow of water exiting on the downstream face or even beyond the toe of the slope. Failures can result in heaving or piping and internal erosion (SRK 1986). The following practical considerations should be noted:

- the head at which seepage erosion failure occurs depends on the soil type. The amount of fines in the soil, the specific gravity and the porosity of the soil play the most important role,
- discontinuities can lead to concentrated seepage (piping) and increased probability of failure, and
- the mode of seepage erosion failure depends on the soil type, the rate of head increase and the flow condition (e.g., saturated or unsaturated flow). The soil type controls whether heave is followed by a quick condition as in clean sand, or whether heave leads to crack formation, concentrated flow and piping. The latter mode appears to be more prevalent in granular soils with a large percentage of fines.

The rate of head increase determines whether the seepage erosion is manifested by a quick condition on the soils surface, or whether heave of the soil surface will occur. A quick condition prior to heave can be produced when the head is raised very slowly.

A rapid increase in head results in heaving of the surface, leading eventually to a quick condition.

Under drainage systems may be either continuous blankets of sands and gravels, or slotted or open-jointed pipes laid in gravel. Pipes can in themselves lead to erosion of fines and they need protection by filters of coarse sand or filter fabric, although the long-term integrity of fabrics is questionable. In any case pipe drains should not be used on compressible foundations.

The potential for seepage erosions has been investigated at typical Canadian uranium tailings impoundments. Where till cover have been used in conjunction with sand and gravel outer zones the likelihood of seepage erosion is very remote. Even if cracking as a result of differential settlement were to occur most tills have self-healing characteristics, depending on their gradation. Where tailings have been placed directly against waste rock critical conditions can arise. Potential for erosion also exists with sloping core dams and filter blankets underlying the embankment, and with semi-dry tailings provided with an underdrainage system. Seepage erosion can be virtually discounted as a failure mechanism if on decommissioning the tailings impoundment is entirely covered with a low permeability material protected from surface erosion. By this mean the quantity of infiltrating water and more importantly the hydraulic gradients that cause seepage erosion are minimized.

Almost everything that has been said about embankments applies to low height dykes and saddle dams, although some relaxations can be afforded depending on site specific conditions, since loads vary as a function of the square of the height of confinement.

7.1.4 LESSONS FROM FAILURE OF EARTH DAMS

Pierre Londe, the French dam expert, has identified 3 principal categories of failure of earth dams:

- overtopping (30%),
- seepage and piping (35%), and
- sliding (15%).

The remainder are miscellaneous or unknown.

Failure by overtopping points to inadequate spillway capacity or misoperation of spillway gates. Often too little is known about river flood conditions.

Failures by seepage are mainly a result of piping of fine grained soil through joints in rock, through rockfill embankment zones or along buried conduits. Proper design and construction of filters is vitally important.

Failures by sliding tend to be due either to failure in overconsolidated clay-shale foundations, or as a result of liquefaction of silts and fine sands. The probability of failure of a long dam is much higher than that of a short dam, because of the difficulty and expense of adequately investigating the foundations of the former.

Londe has put forward ten recommendations for improving overall safety in the design, construction and operation of earth for water retention dams. Many of these rules are applicable either directly or with modifications to impoundments for tailings. There are as follows:

- be aware, of even thin, seams of over-consolidated clay-shale in formations, but if they exist design for them using residual shear strength parameters,

- investigate for loose silts or sands, and study their liquefaction potential,

- thorough analysis of the frequency of floods and probability of downstream damage is required,

- for spillway and outlet design use recent hydrologic methods with a clear appraisal of the consequence of overtopping,

- ample and well graded filters and drains are required to prevent piping through a dam and its foundations,

- all fine clay soils for use in the core of a dam should be tested for dispersion of clay particles,

- build instrumentation into the dam to monitor for safety, and
- provide thorough and careful surveillance of dams and appurtenant structures on a continuing basis with automatic recording equipment.

7.2 DIVERSION WORKS AND SPILLWAYS

Tailings impoundments should not be located in natural water courses, but if it is necessary to be in a small streambed, it has to be diverted around the disposal area. Furthermore some extent of catchment area will always contribute runoff to the impoundment.

7.2.1 DIVERSION DITCHES

Diversion ditches around the impoundment and spillways to handle water flowing into the pond are required.

Embankments should be designed with a freeboard of between 1 and 3 m to prevent overtopping due to wave runup. The freeboard depends on the fetch distance. This information together with the size of flood to be handled enables the depth and length of the spillway channel to be calculated. A simple method uses the formula for a board-crested weir (CANMET 1977). Some additional factor needs to be applied to the flood flow to allow for mill production flow, although this may be no more than 5-10%.

Where complete diversion around a tailings impoundment has been provided, a spillway can often be eliminated merely by building extra freeboard into the embankments or dykes to allow for peak precipitation falling directly onto the impoundment.

Diversions, culverts and other closed conduits are unlikely to function satisfactory, in the long-term due to their tendency to plug with debris. Under West Coast conditions even culverts as large as 5 m diameter have been known to jam with forest debris during torrential downpours. Also concrete and other manufactured linings for open channels tends to be unreliable in the long-term because of maintenance requirements. The manual on linings for irrigation canals, (USBR 1963), provides useful construction ideas, some of which may be applicable to uranium impoundment diversions under certain circumstances.

The use of probable maximum precipitation (PMP) for design rainfall and probable maximum flood (PMF) for design flood is common now, (Walters et al 1986). The rationale for the use of PMP is discussed later under flood erosion, see Section 8.3.1.1.

Flow characteristics in diversion ditches are determined by channel geometry, such as gradient, hydraulic roughness and changes in section. Most methods of design of riprap channel lining are based on mild channel gradients, where flow is subcritical at Froude Numbers less than 0.8. For steeper gradients, greater than about 10%, the riprap size may be greater than the depth of flow. Alternatively, a series of channel drop structures located *en echelon*, each no more than 1 m high, can be used. The drop structures act as energy dissipators allowing smaller sized riprap to be used on the channel bed. Loose rock drop structures should not be used. They should be either cement bound masonry or reinforced concrete, or possibly gabions or reinforced rockfill, (Stephenson 1979), although durability is a serious problem. Loose rock check claims, designed to serve similar purposes in mountain creek regulation works, are notorious for failing during torrential floods: early experience in both Europe and in California have proved this. Often this occurs as a result of a scour pool forming at the base of the drop structure.

Channel transitions accommodate changes in direction, gradient and section of the diversion ditches, but they change flow behaviour and careful attention needs to be paid to design details. Riprap lined channel bends should have a radius of curvature equal to at least twice the top width and not less than 15 m.

The most critical point in designing spillway and diversion ditches is usually preventing erosion of the toe of embankments. This can be achieved by reducing flow velocities using flat gradients or drop weirs, and by the use of protective riprap or gabions. Flow velocities should not be reduced to such low values that sedimentation takes place, and preferably some self-scouring potential of fine material should be designed for.

In addition diversion ditches should have ample width to allow for partial blockage by ice and to prevent blockage by debris. With the development of forest cover, particularly alongside the diversion channels, the potential for forest debris production and consequent blockage increases. Clearly therefore the design of diversion ditches for long-term maintenance free operation is a difficult task, and the best approach is to select a site and impoundment design that requires minimal diversion capability in the first place.

7.2.2 SPILLWAYS

Spillway structures are provided to decant flows from the entire catchment area beyond the tailings impoundment. However, if spillways become blocked, storm runoffs discharge over the embankments resulting in an increased susceptibility to gully erosion.

The methods used for estimating gully erosion of covers and embankment slopes are not considered appropriate for erosion estimates when large flows occur. Temporarily increased flows may result as the embankment crest breaches, releasing stored water. Rapid erosion is anticipated, leading to embankment failure. The long-term stability of the embankment is therefore dependent on the long-term functioning of the spillway. Experience in the maintenance of water retaining dam spillways has indicated a high likelihood of at least temporary failure due to:

- vegetation growth in the spillway,
- debris blockage (Beaver dams or natural debris accumulation),
- ice blockage, and
- sedimentation in the flow channel upstream of the spillway, blocking off flow to the spillway.

Erosion as a consequence of diversion structure failures of existing impoundments, following channel blockage by either organic or inorganic debris or ice, is a potential cause of major uranium tailings releases (SRK 1986). The failure potential can only be minimized by periodic on-going maintenance, or complete redesign with heavy embankment armouring as backup protection.

7.3 BARRIERS TO SEEPAGE

7.3.1 OVERVIEW

Barriers to seepage can be placed into one of two categories: those which minimize infiltration of water into the tailings area (surface cap) and those which minimize exfiltration of water from the tailings (bottom liner). The barriers to infiltration include covers such as vegetation, soil, waste rock, synthetic liners, engineered caps and tailings. Barriers to exfiltration include synthetic membranes, low permeability placed soil layers, or low permeability natural in-place materials such as bedrock and glacial till.

Physico-chemical barriers both modify the chemical composition of seepage and retard the migration of contaminants from a site. These are barriers to contaminant migration and not necessarily seepage flow. The most common materials are peat, glacial till, clays, sands, and to some extent, rock.

The technology for selection and design of these barriers is reviewed in this section; where the technology has or could be applied is discussed.

7.3.2 INFILTRATION BARRIERS

Seepage from a tailings impoundment can be controlled by preventing infiltration into the impoundment or seepage away from the impoundment. If infiltration exceeds seepage then this adds to the volume of solution stored in the impoundment. In the long-term the seepage away from the impoundment must balance the infiltration into the impoundment, the effect of storage becoming negligible. Seepage, in the long-term, is controlled by controlling infiltration.

Infiltration is defined as the passage of water through the surface of the soil, via pores or small openings, into the soil profile. It is one of the most important components of the hydrologic cycle. The ability of water to move through a soil profile has a direct effect on many of the other components of the hydrologic cycle. The main components of the hydrologic cycle are climatic conditions, evapotranspiration, interception, detention storage, infiltration, overland flow, subsurface flow, surface storage, deep percolation, ground water flow and streamflow. Infiltration directly affects subsurface flow, deep percolation, (see Figure 7.3-1) ground water flow and surface runoff. Available water in the soil profile has a major influence on the vegetative growth and therefore, influences evapotranspiration, interception, and surface storage.

7.3.2.1 Vegetation

Vegetative cover affects infiltration and recharge into a tailing area. Table 7.3.1 shows relative infiltration rates for various soil textures and cover conditions. Bare soil, or tailings, has the least infiltration, with denser vegetative cover providing more infiltration. Finer textured soils possess a lower infiltration rate. The difference in infiltration between coarse and fine textured soils varies by about one order of magnitude, a much lower variation than would be expected on the basis of soil permeability alone. The difference is attributed to secondary soil structure and the promotion of infiltration by soil suction. Suction is greater in the fine grained, low permeability soil and reduction in flow by low permeability is in part offset by higher initial suction.

The relative effect of vegetation on reducing the net infiltration (infiltration-evapotranspiration) is site-specific and depends upon climatic factors, vegetation types, soils types, etc. As a general rule vegetation will reduce direct runoff and may well lower seepage rates if evapotranspiration rates from the vegetated surface are greater than the increase in infiltration rates resulting from reduced runoff. Experience at Elliot Lake has not shown major differences in outflow rates from vegetated and unvegetated tailings facilities. To demonstrate the potential benefits of vegetation as a seepage barrier, detailed moisture balance calculations would be required. The major problems in these calculations is determining valid parameters for the vegetation type, condition, percent cover, etc. at a future closed facility. Models such as the U.S. Army Corps of Engineers HELP can be used as a screening tool to determine the potential benefits of a vegetative cover, (Schroeder et al 1984).

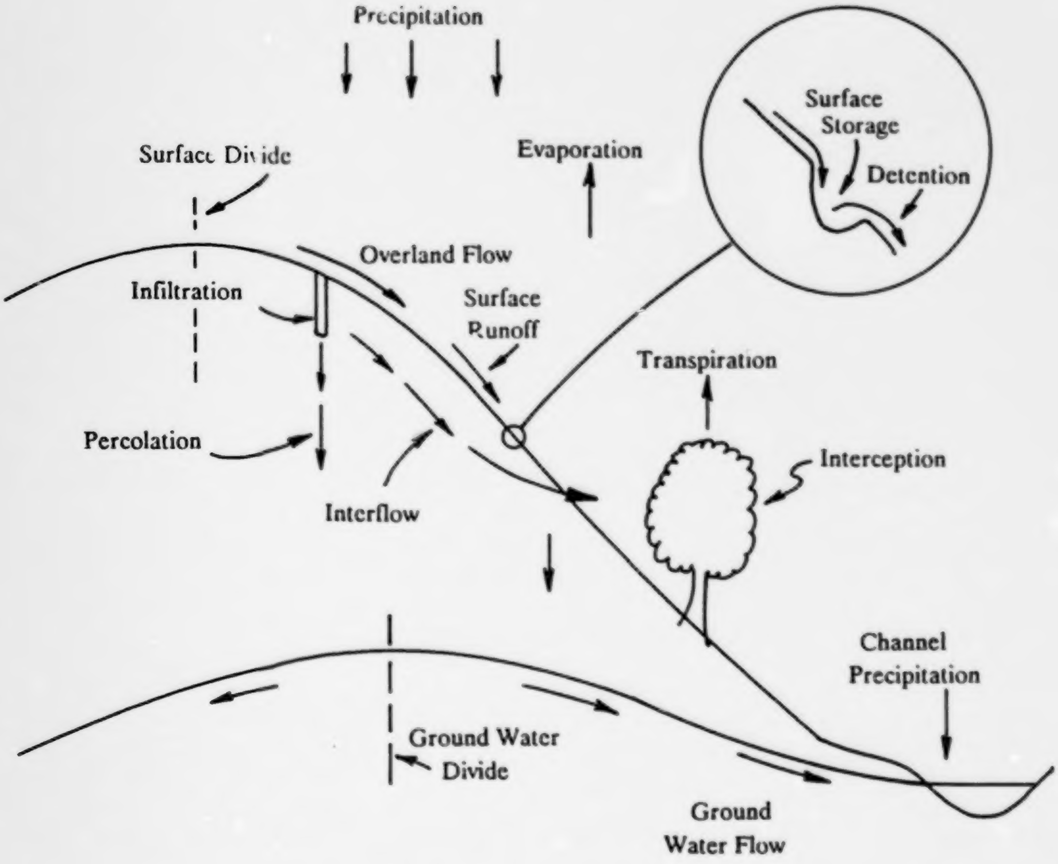

Precipitation
Surface Storage
Detention
Surface Divide
Evaporation
Overland Flow
Infiltration
Surface Runoff
Transpiration
Percolation
Interception
Interflow
Channel Precipitation
Ground Water Divide
Ground Water Flow

Figure 7.3-1 The Hydrologic Cycle

TABLE 7.3-1
NET INFILTRATION RATES FOR UNFROZEN SOILS
(inches per hour)
(Gray 1970)

	Ground Cover Conditions					
Soil Profile Category	Bare Soil	Row Crops	Poor Pasture	Small Grains	Good Pasture	Forested
I	0.3	0.5	0.6	0.7	1	3
II	0.1	0.2	0.3	0.4	0.5	0.6
III	0.05	0.07	0.1	0.15	0.2	0.25
IV	0.02	0.02	0.02	0.02	0.02	0.02

Category I:	Coarse and medium textured soils over sand and gravel, glacial outwash materials or, coarse, open, till or, coarse alluvial deposits
Category II:	Medium textured soils over medium textured till
Category III:	Medium and fine textured soils over fine textured clay till
Category IV:	Soil over shallow bedrock (two feet or less).

7.3.2.2 Engineered Caps

The design of an engineered cap depends upon numerous factors including: the size of area to be covered; the trafficability and support requirements of the waste and of the final cover; environmental factors such as freeze/thaw or dry/soak cycles; potential for cracking and differential settlements; erosion from wind and water; vegetation requirements and aesthetics; the protection of the hydraulic barrier from animals, roots, or other hazards; the control of gases such as radon and methane; and most importantly, the permanent objectives for the cover.

Covers for uranium tailings areas are typically applied at the decommissioning stage as a long-term management strategy. Construction materials most suited to these applications are natural materials. Man-made materials such as polymenic liners, are not precluded from use, but their life is substantially less than natural materials.

The prime purpose of covers at tailings sites has been to stabilize the surface, reduce radon emissions, minimize infiltration and control gamma radiation. Several American sites have been covered but in Canada, no cover has been placed to date over a tailings repository to control infiltration, however, infiltration barriers have been proposed (Key Lake 1979).

Experience gained from landfill covers demonstrates that single component soil covers, even if comprised of clays, may not be efficient at reducing infiltration. Recent studies have shown that infiltration rates in a clay lined landfill site with 2-3 metres of cover were measured at 25% of the annual precipitation, (Hims et al 1984). This level is not greatly lower than would be expected in an uncovered site. High infiltration rates through these impervious covers is attributed to cracking from freeze/thaw and wet/dry cycles as well as differential settlement of the waste materials. Similar problems with infiltration have been reported at covered low-level radioactive waste disposal sites (SENES 1984).

The current trend in cover design for minimizing infiltration is to apply a multi-layered engineered cap. This cap would normally include a vegetated surface soil layer, a drainage layer, and/or capillary break and an hydraulic barrier. In some cases an intrusion or erosion resistant barrier may also be considered. This barrier could be crushed rock and placed either on the surface or as part of the drainage layer.

The design of the cover should be centred around the locally available construction materials. The uranium mining districts typically contain suitable sands and gravels and rock for riprap or erosion protection, but low permeability barrier materials are not normally present. Low permeability soils used in dam construction include glacial tills with permeabilities in the range of 1 x 10^{-7} m/s. The EPA define soils with low permeability (impervious soils) as having a permeability of 1 x 10^{-9} m/s. Depending upon the performance objectives of the infiltration barrier, these local tills may suffice as the hydraulic barrier. If not, experience has demonstrated that these soils can be modified to low permeabilities by adding small amounts of bentonite.

To demonstrate the effectiveness of infiltration barriers, model runs have been completed for a generic facility in the Elliot Lake, Ontario and Uranium City, Saskatchewan areas.

7.3.3 DEMONSTRATION OF THE PERFORMANCE OF INFILTRATION BARRIERS

This section describes example calculations as to how these technologies will impact the amount of seepage reporting for uranium tailings sites. The basic tailings basin impoundment type and cover examples selected, are applicable to any tailings facility in Canada.

The Hydrologic Evaluation of Landfill Performance (HELP) program was used to estimate the surface runoff, subsurface drainage, and seepage that may be expected from of a wide variety of cover designs. This model may not be a suitable design tool for the final selection of a layered cap but is useful as a screening tool to assess the benefits and effects of alternative cover designs. The program models the effects of hydrologic processes including precipitation, surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage using a quasi-two-dimensional approach.

Climatological data requirements include daily precipitation, mean monthly temperatures, mean monthly isolation (solar radiation) in langleys, leaf area indices, and winter cover factors. The data may be entered manually or selected from built-in default data files. Default climatological data are available in the HELP model for over a hundred cities. The precipitation data base is limited to five years of daily records.

If the default climatologic or soil data options in the model are used, acceptable default types of vegetation are bare ground (i.e. no vegetation); excellent, good, fair and poor stands of grass; and good and fair stands of row crops.

For the example calculations, the following conditions are modelled:

i) bare tailings,
ii) vegetated tailings,
iii) soil covered tailings,
iv) waste rock/gravel, and
v) engineered cap.

7.3.3.1 Elliot Lake

The results of the infiltration modelling runs are discussed below.

i) Bare Tailings

Bare tailings can be expected to have high runoff rates, modest evapotranspiration losses and substantial net infiltration or seepage. With an unvegetated surface, the Soil Conservation Service (SCS) curve number can be expected to be quite high. For the example model runs, runoff, evaporation and seepage rates account for 19%, 63.5% and 17.5% of the annual precipitation respectively. When the tailings permeability was increased by a factor of 3, runoff rates decline by 3% and seepage rates increase by 3%. The results are summarized on Figure 7.3-2.

ii) Vegetated Tailings

Vegetation has a marked effect on the water balance at a tailings site. With the growth of vegetative cover, runoff rates decrease from 19% to 9% of the annual precipitation while evapotranspiration increases from 63.5% to 73.6%. The major finding is that seepage rates are not changed. With a good vegetative cover, runoff rates are again reduced further to 3.3% of the annual precipitation. Although evapotranspiration rates are increased, this may not offset the reduced runoff. This is not to conclude that this phenomenon is universally applicable to all sites. The results are summarized on Figure 7.3-3.

iii) Soil Cover

Direct application of soil to the tailings area surface may have mixed effects. If the soil retains its low permeability, runoff will increase substantially and seepage rates will be greatly reduced. A compacted till cover with a permeability of 2×10^{-8} m/s will reduce seepage rates to less than 2% of the annual rainfall. If this cover cracks and weathers (as is expected) infiltration rates increase substantially. The example as shown below indicates that if the effective permeability of the cover increases to 1×10^{-6} m/s, seepage rates exceed those for bare tailings. The increased permeability results in a major reduction in the rate of surface runoff. The results are summarized on Figure 7.3-4.

iv) Rock/Gravel Cover

Rock or gravel is often applied to stabilize the surface of a tailings area. This pervious layer effectively eliminates runoff and therefore can substantially increase infiltration rates. For the modelled case, the rock/gravel cover increases seepage rates from 17.5% to 37.8%. This is more than a factor of 2 and further demonstrates how the permeability of the surface layer can affect the overall amount of seepage produced. The results are summarized on Figure 7.3-5.

v) Engineered Cap

A properly constructed engineered cap can greatly reduce infiltration rates. The example modelled includes a cap with one metre of soil for frost protection and vegetation, 0.3 metres of lateral drainage layer, and one metre of a low permeability seepage barrier. The lateral drainage layer would also include farm tiles to conduct water from the surface of the disposal area. This cap reduces surface runoff to 3.1% of the annual rainfall. The lateral drain intercepts 19.4% while evapotranspiration accounts for 70.9% leaving 6.6% as seepage. This is a 62% reduction in the total seepage as compared with bare or vegetated tailings. The major finding is that these layers are effective but not 100% efficient in limiting seepage. At 6.6% infiltration this represents approximately 60 mm of precipitation or 60,000 m^3/yr from a 100 ha disposal site. The results are summarized on Figure 7.3-6.

Rock/gravel surface layers have a major effect, increasing the infiltration. With a pervious surface zone, the lateral drains become more efficient reducing the seepage rates.

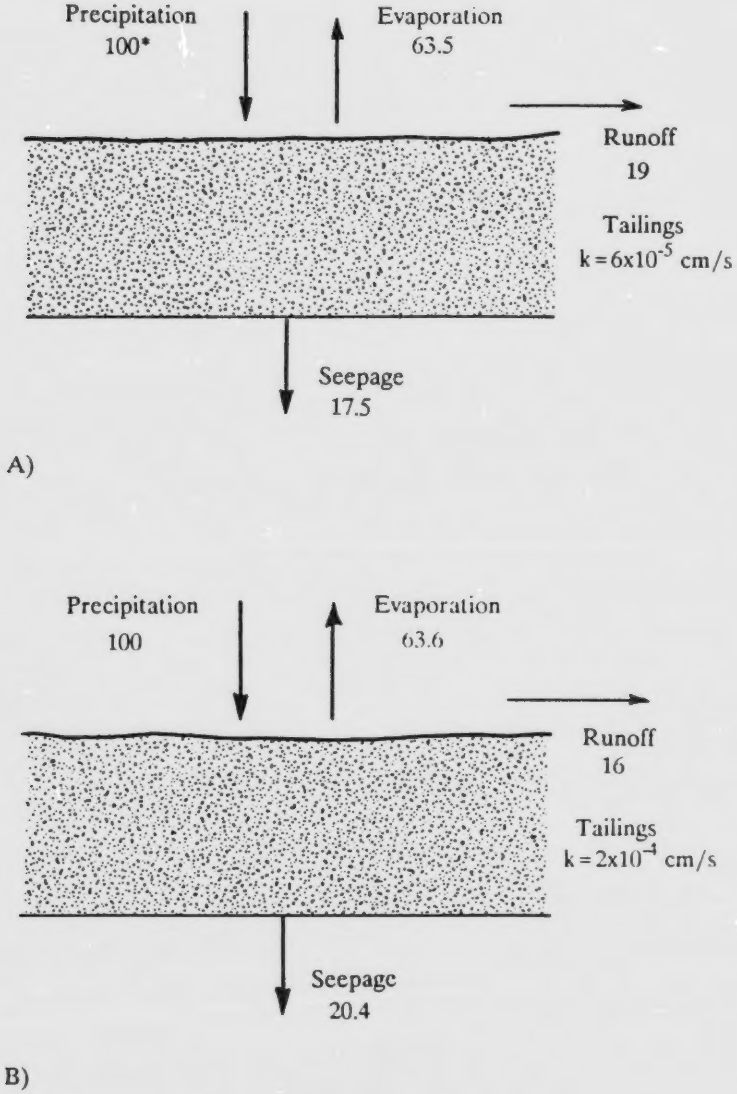

Precipitation
100*
Evaporation
63.5
Runoff
19
Tailings
k=6x10^{-5} cm/s
Seepage
17.5
A)
Precipitation
100
Evaporation
63.6
Runoff
16
Tailings
k=2x10^{-4} cm/s
Seepage
20.4
B)

Figure 7.3-2 Infiltration Barriers for Bare Tailings - Elliot Lake

Note:

1. (*) Numbers are percent of total annual precipitation

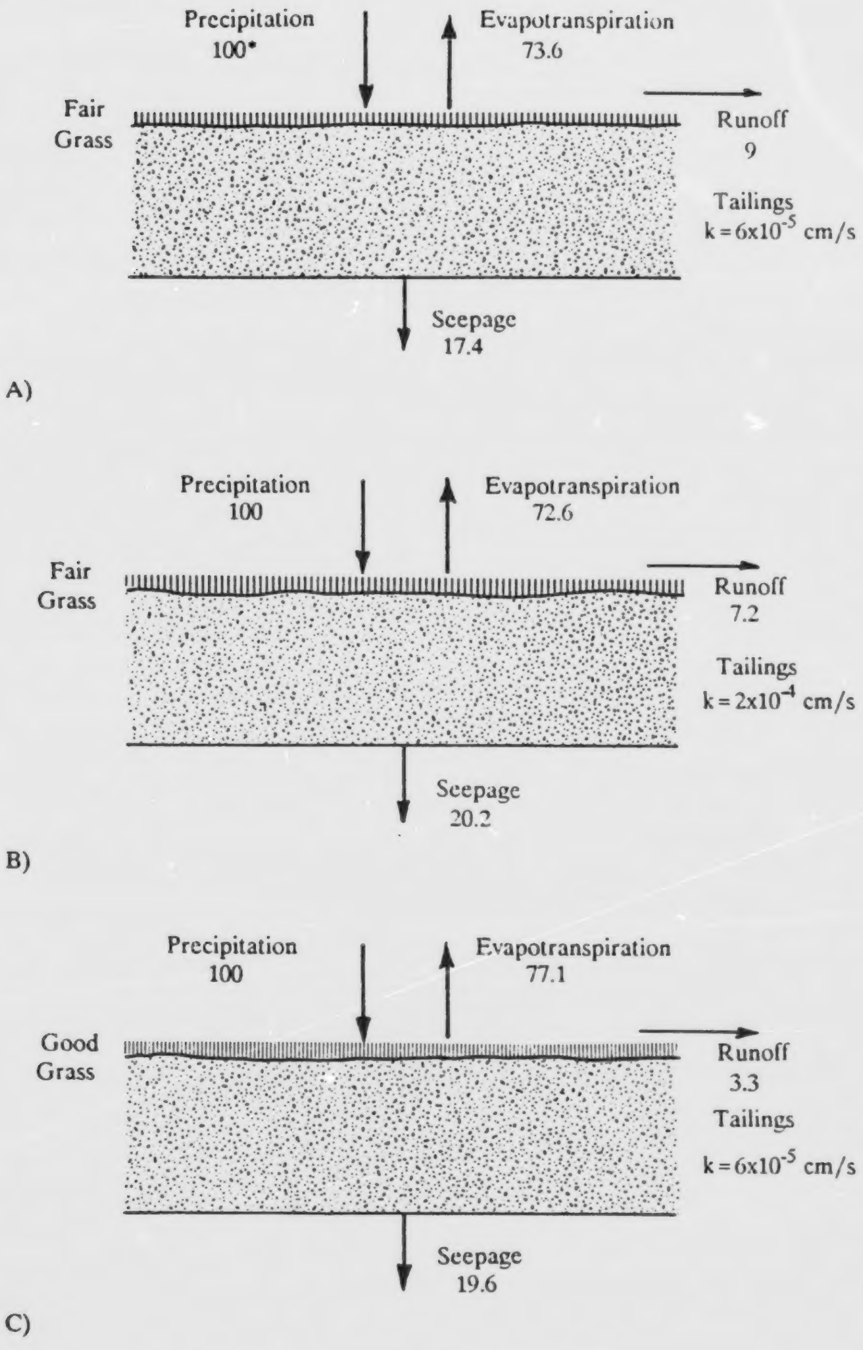

Precipitation 100*
Evapotranspiration 73.6
Fair Grass
Runoff 9
Tailings k = 6x10^{-5} cm/s
Seepage 17.4
A)
Precipitation 100
Evapotranspiration 72.6
Fair Grass
Runoff 7.2
Tailings k = 2x10^{-4} cm/s
Seepage 20.2
B)
Precipitation 100
Evapotranspiration 77.1
Good Grass
Runoff 3.3
Tailings
k = 6x10^{-5} cm/s
Seepage 19.6
C)

Figure 7.3-3 Infiltration Barriers for Vegetation Cover - Elliot Lake

Note:

1. (*) Numbers are percent of total annual precipitation

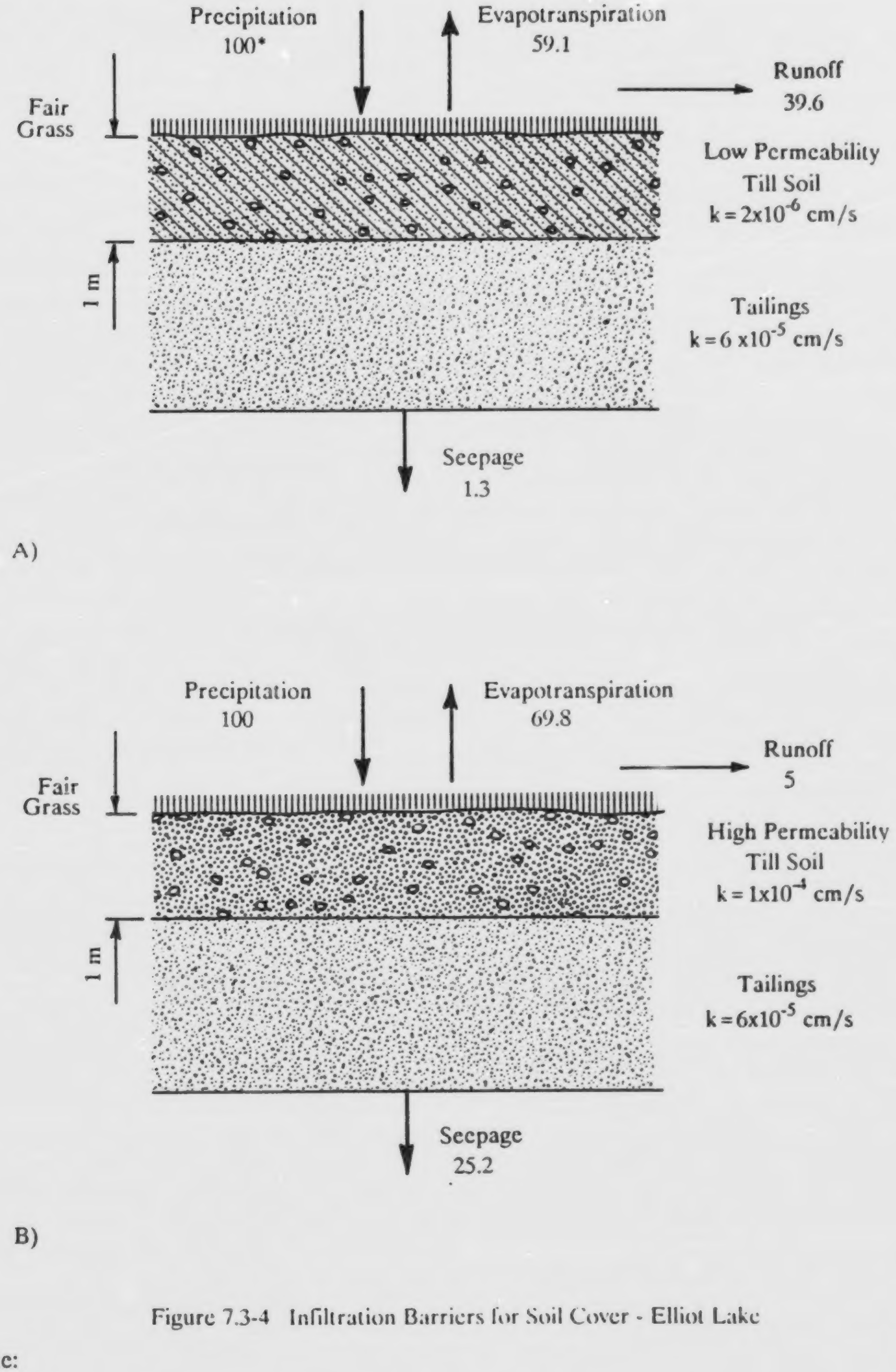

Precipitation
100*
Evapotranspiration
59.1
Runoff
39.6
Fair
Grass
Low Permeability
Till Soil
k = 2x10^-6 cm/s
1 m
Tailings
k = 6 x10^-5 cm/s
Seepage
1.3
A)
Precipitation
100
Evapotranspiration
69.8
Runoff
5
Fair
Grass
High Permeability
Till Soil
k = 1x10^-4 cm/s
1 m
Tailings
k = 6x10^-5 cm/s
Seepage
25.2
B)

Figure 7.3-4 Infiltration Barriers for Soil Cover - Elliot Lake

Note:

1. (*) Numbers are percent of total annual precipitation

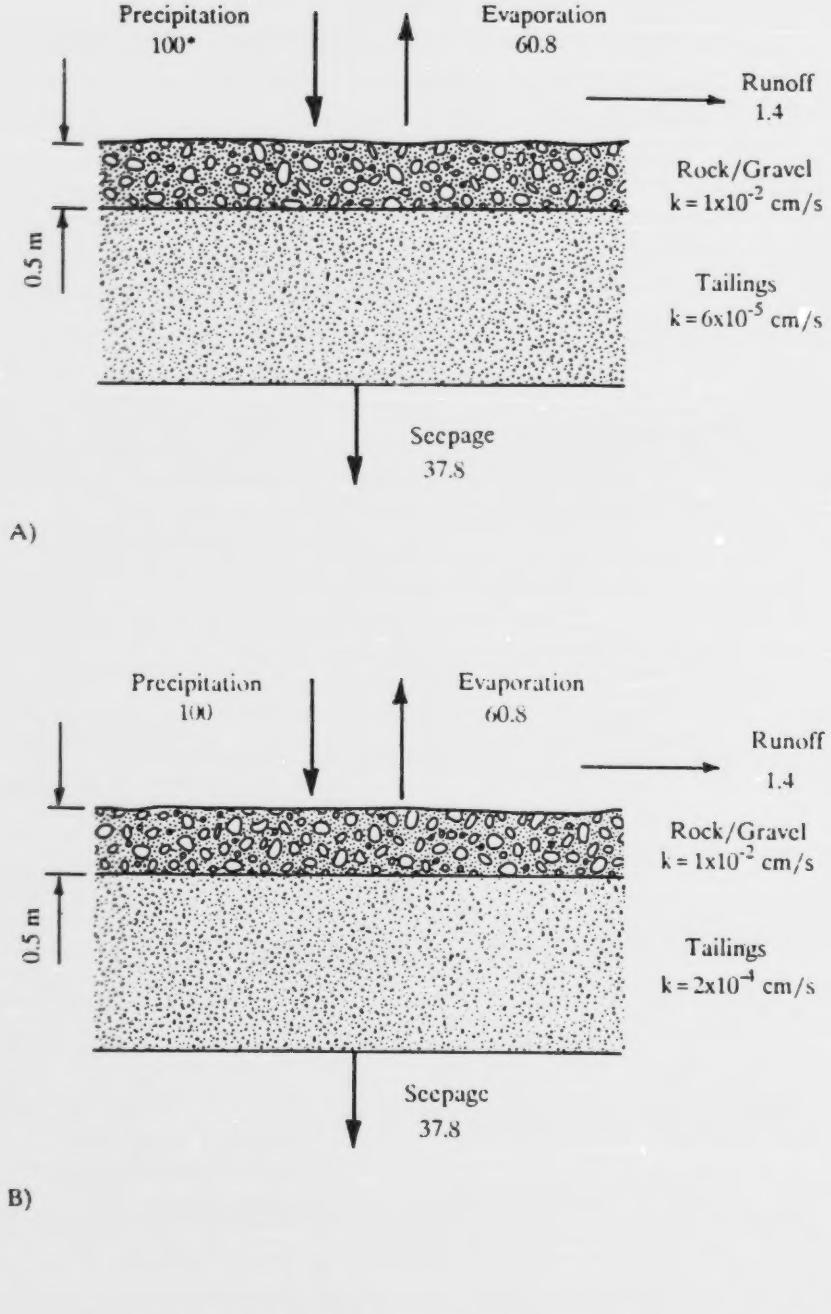

Precipitation
100*
Evaporation
60.8
Runoff
1.4
Rock/Gravel
k = 1x10^-2 cm/s
0.5 m
Tailings
k = 6x10^-5 cm/s
Seepage
37.8
A)
Precipitation
100
Evaporation
60.8
Runoff
1.4
Rock/Gravel
k = 1x10^-2 cm/s
0.5 m
Tailings
k = 2x10^-4 cm/s
Seepage
37.8
B)

Figure 7.3-5 Infiltration Barriers for Rock/Gravel Cover - Elliot Lake

Note:

1. (*) Numbers are percent of total annual precipitation

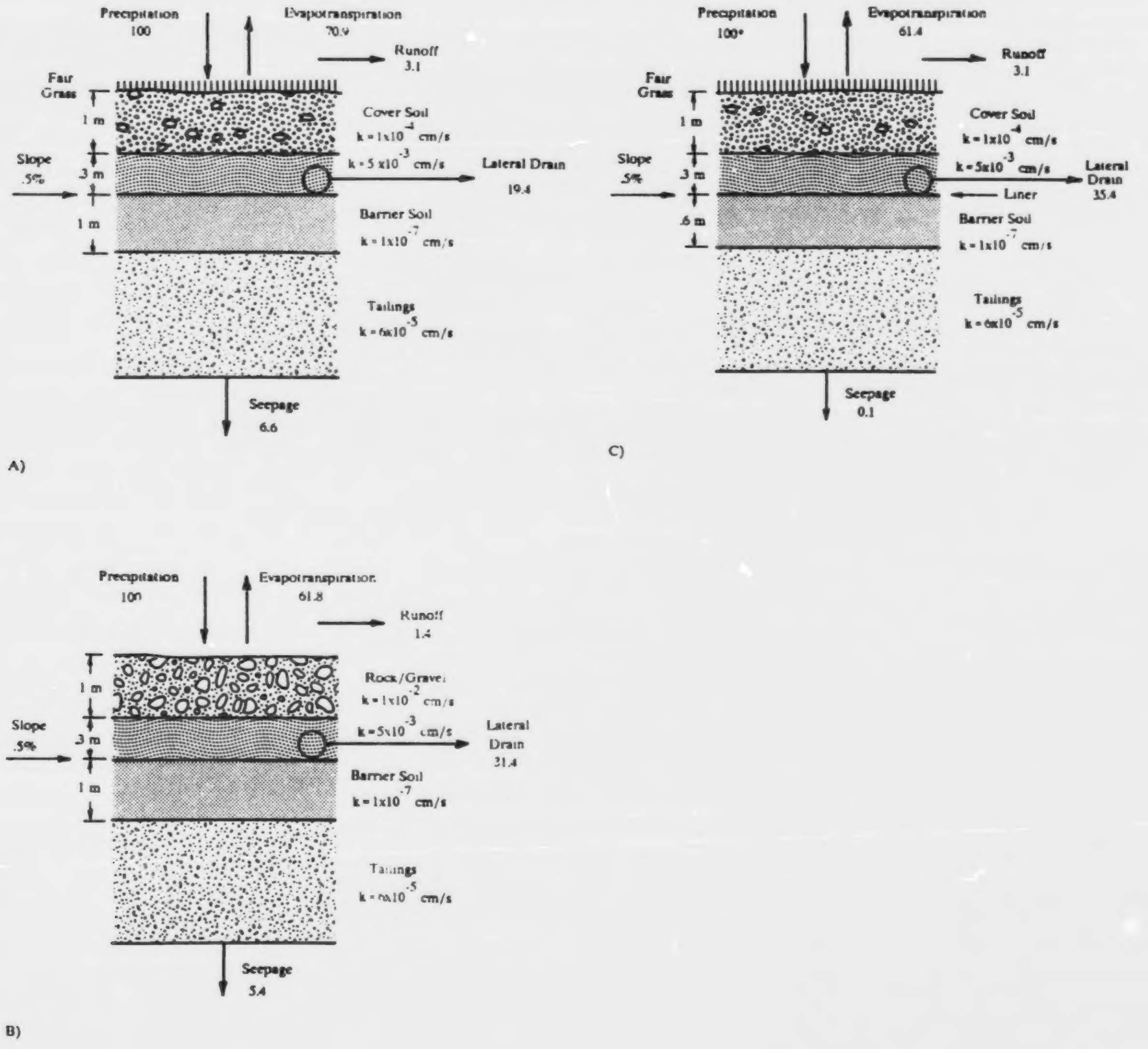

Precipitation
100
Evapotranspiration
70.9
Runoff
3.1
Fair Grass
1 m
Cover Soil
k = 1x10^-4 cm/s
Slope
.5%
.3 m
k = 5 x10^-3 cm/s
Lateral Drain
19.4
1 m
Barrier Soil
k = 1x10^-7 cm/s
Tailings
k = 6x10^-5 cm/s
Seepage
6.6
A)
Precipitation
100*
Evapotranspiration
61.4
Runoff
3.1
Fair Grass
1 m
Cover Soil
k = 1x10^-4 cm/s
Slope
.5%
.3 m
k = 5x10^-3 cm/s
Lateral Drain
35.4
Liner
.6 m
Barrier Soil
k = 1x10^-7 cm/s
Tailings
k = 6x10^-5 cm/s
Seepage
0.1
C)
Precipitation
100
Evapotranspiration
61.8
Runoff
1.4
1 m
Rock/Gravel
k = 1x10^-2 cm/s
Slope
.5%
.3 m
k = 5x10^-3 cm/s
Lateral Drain
31.4
1 m
Barrier Soil
k = 1x10^-7 cm/s
Tailings
k = 6x10^-5 cm/s
Seepage
5.4
B)

Figure 7.3-6 Infiltration Barriers for Engineered Cap - Elliot Lake

Note:

1. (*) Numbers are percent of total annual precipitation

An engineered cap with a synthetic membrane liner is by far the most effective short-term infiltration barrier. The seepage rates predicted for an engineered cap with a liner that was 99 percent efficient are 0.1% of the annual rainfall. The life of the liner, however, needs to be considered.

7.3.3.2 Northern Saskatchewan

The results of the infiltration modelling runs are discussed below.

i) Bare Tailings

Bare tailings in northern Saskatchewan have very different infiltration characteristics compared with bare tailings at Elliot Lake. Runoff rates are much lower and evapotranspiration rates much higher. This would appear to be the result of lower rainfall, more potential evaporation and lower rainfall intensities. Seepage levels on bare tailings are similar to the Elliot Lake impoundments. The results are summarized on Figure 7.3-7.

ii) Vegetated Tailings

Vegetation is a very useful tool in northern Saskatchewan for reducing net infiltration. Because of the high level of potential evaporation, vegetation reduces seepage rates from 16.3% of the annual infiltration to 10.7%. This compares with the situation at Elliot Lake where vegetation has little effect on seepage rates. The results are summarized on Figure 7.3-8.

iv) Rock/Gravel Cover

A rock/gravel cover will virtually eliminate surface runoff and increase seepage rates, see Figure 7.3-9.

v) Engineered Caps

The results indicate that engineered caps are not very effective in reducing the net infiltration at the northern Saskatchewan tailings area. In fact, the results for the infiltration through an engineered cap are only marginally lower than for vegetation alone. With the engineered cap, runoff is reduced to zero, however, the water passing through the surface zone is not efficiently collected by lateral drains. This is because only a small amount of water reaches the lateral drains (60 to 70 mm/yr) therefore the gradients to drive flow to the drain are very low. Much of the infiltrating water passes vertically down through the impervious soil zone into the tailings. The results are summarized on Figures 7.3-10 and 11.

Summary

The net infiltration of precipitation into tailings areas is site-specific and depends upon the nature of the tailings, surface cover and climatic conditions. The HELP model assumes saturated ground conditions at the commencement of precipitation. Clearly antecedent moisture conditions could influence results significantly. If for example 0.5 m of clean, sand and gravel or waste rock cover having a void ratio of 0.30 were to be saturated with 100 mm of rain following a dry period, the cover might easily absorb the bulk of the rain with only small losses to runoff and evaporation. In that instance the majority of the precipitation would infiltrate through the tailings. Seepage might then be in the range of 60% to 80%. Nevertheless, infiltration models may be useful as a screening tool to assess the benefits of various cover technologies on the overall performance of the system. A model that simulates unsaturated conditions called SOILMOIST has been developed for the UMTRA program and this may yield more realistic results under certain conditions.

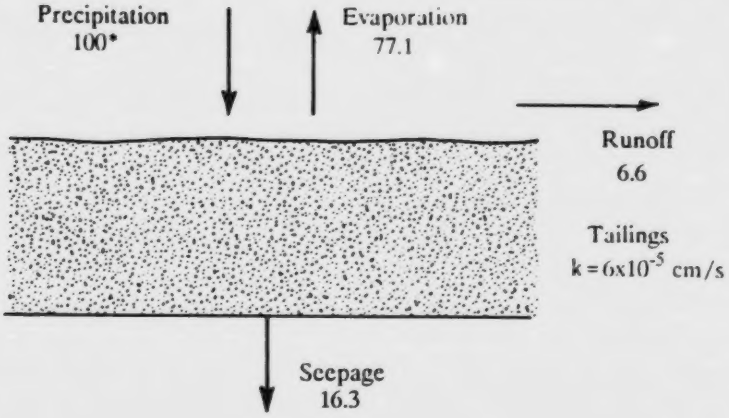

Precipitation
100*
Evaporation
77.1
Runoff
6.6
Tailings
k=6x10^-5 cm/s
Seepage
16.3

Figure 7.3-7 Infiltration Barriers for Bare Tailings - Northern Saskatchewan

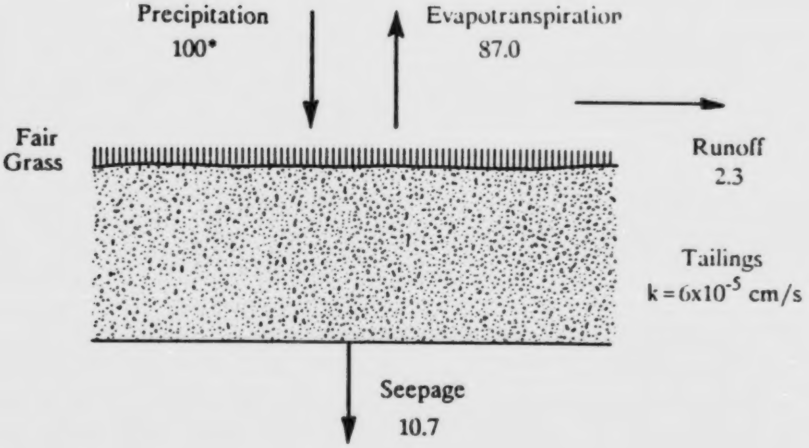

Precipitation
100*
Evapotranspiration
87.0
Fair
Grass
Runoff
2.3
Tailings
k=6x10^-5 cm/s
Seepage
10.7

Figure 7.3-8 Infiltration Barriers for Vegetation Cover - Northern Saskatchewan

Note:

1. (*) Numbers are percent of annual precipitation

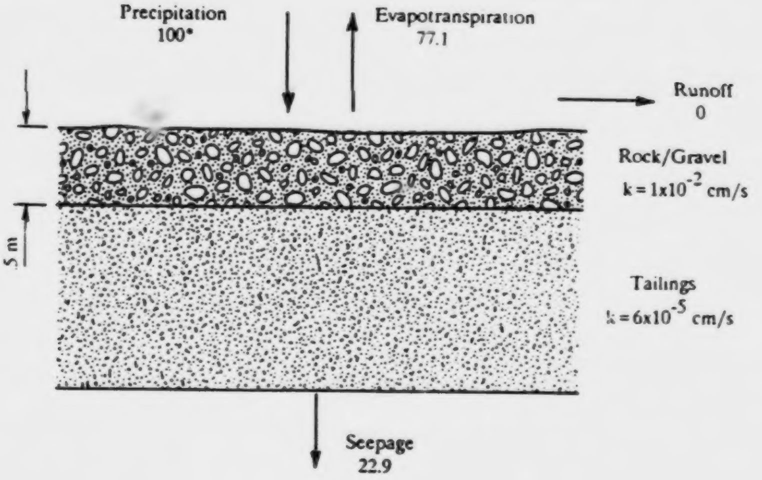

Precipitation
100*
Evapotranspiration
77.1
Runoff
0
5 m
Rock/Gravel
k = 1x10^{-2} cm/s
Tailings
k = 6x10^{-5} cm/s
Seepage
22.9

Figure 7.3-9 Infiltration Barriers for Rock/Gravel Cover - Northern Saskatchewan

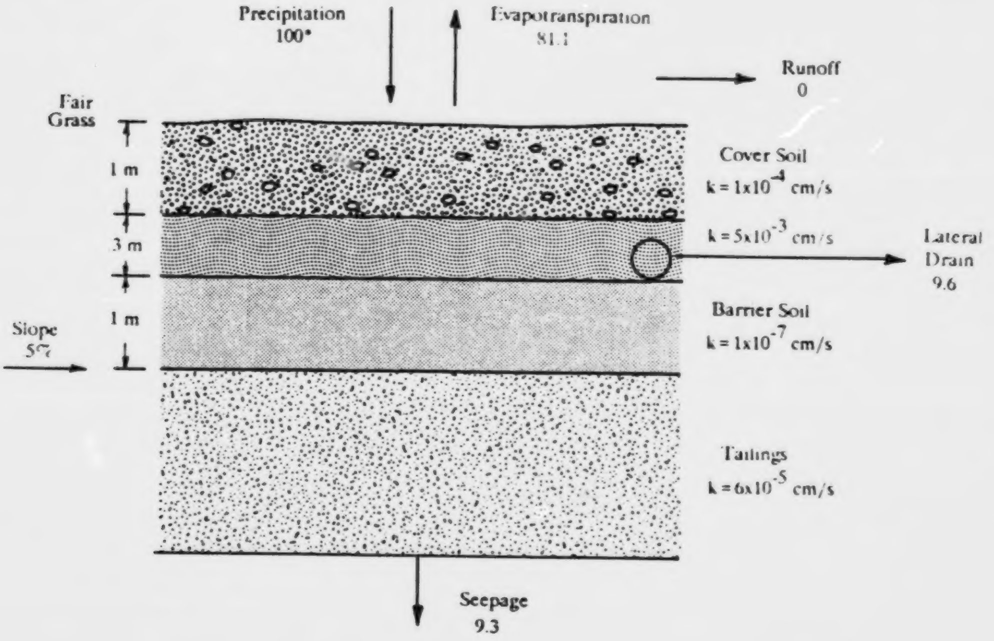

Precipitation
100*
Evapotranspiration
81.1
Runoff
0
Fair
Grass
1 m
.3 m
1 m
Slope
5%
Cover Soil
k = 1x10^{-4} cm/s
k = 5x10^{-3} cm/s
Lateral
Drain
9.6
Barrier Soil
k = 1x10^{-7} cm/s
Tailings
k = 6x10^{-5} cm/s
Seepage
9.3

Figure 7.3-10 Infiltration Barriers for Engineered Cap - Northern Saskatchewan

Note:

1. (*) Numbers are percent of annual precipitation

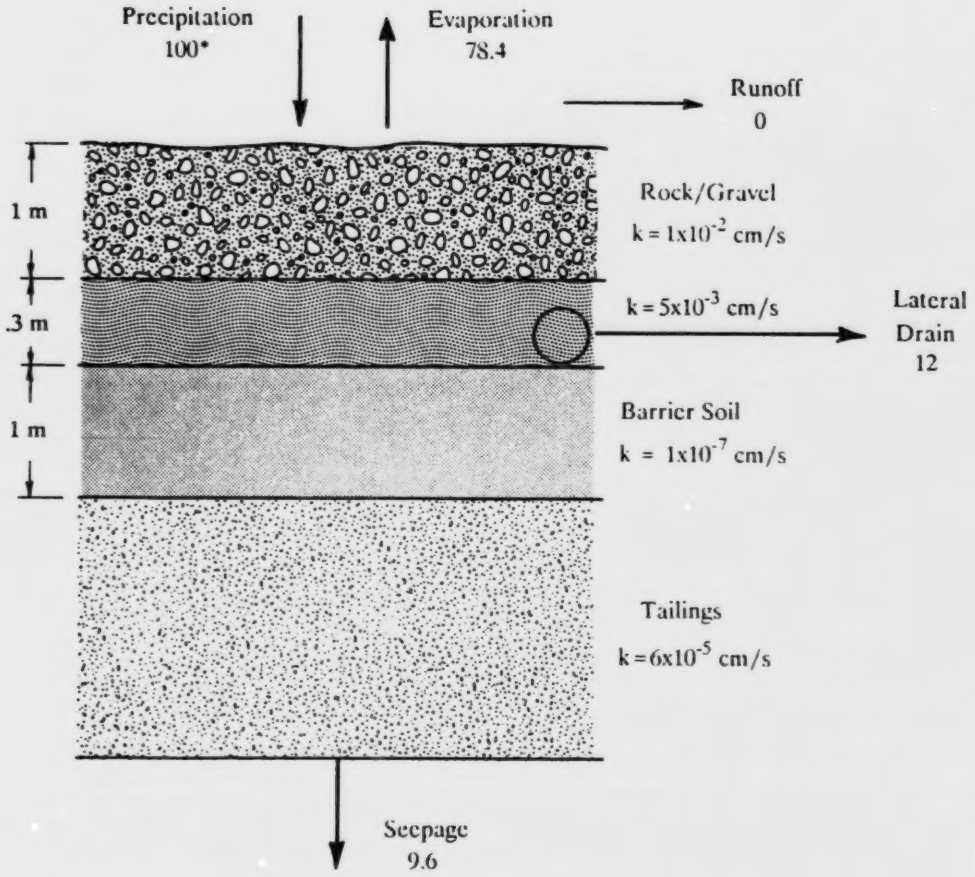

Precipitation
100*
Evaporation
78.4
Runoff
0
1 m
Rock/Gravel
k = 1x10⁻² cm/s
.3 m
k = 5x10⁻³ cm/s
Lateral
Drain
12
1 m
Barrier Soil
k = 1x10⁻⁷ cm/s
Tailings
k = 6x10⁻⁵ cm/s
Seepage
9.6

Figure 7.3-11 Infiltration Barriers for Engineered Cap - Northern Saskatchewan

Note:

1. (*) Numbers are percent of annual precipitation

7.3.4 EXFILTRATION BARRIERS

7.3.4.1 General

Exfiltration is infiltrating water which leaves a tailings repository as leachate or seepage. The seepage occurs as sub-surface flow. Commonly seepage barriers include natural in-place soils and rock or man-made liners. The most common liners at waste management sites are synthetic polymeric liners and low permeability compacted clayey soils. In Canada only one uranium tailings area has been lined, this being the above ground Key Lake tailings facility. All basins constructed since 1970 have seepage controls, but these controls are typically cutoff walls or till cores constructed to bedrock. These seepage barriers are in the outlet valleys of the impoundment areas normally at dam sites .

Man-made liners at uranium tailings areas have both positive and negative effects. During the operation, a liner controls seepage and permits seepages to be intercepted and treated. Liners in combination with underdrainage systems are beneficial in tailings dewatering and consolidation, both during operation and decommissioning. With the liner, water is retained in the tailings basins generally causing high water tables. This can be an effective control mechanism for acid generation as well as greatly reducing radon emissions. The biggest drawback is that the tailings areas become "bathtubs" which, if infiltration exceeds seepage, eventually overflow. Therefore instead of having infiltrating waters exit as seepages, these waters report as surface discharges. In many instances sub-surface flows are desirable as the pathway distance to man is increased and the soils tend to retard the radionuclide migration from the site. Where an infiltration barrier is applied, the underdrain is normally designed to pass infiltrating water so that the basin does not have surface discharge.

In the design of a liner, consideration must be given to several factors including the chemistry of the tailings fluids, the foundation conditions, and performance objectives. An evaluation of earth material liners and synthetic liners for use in uranium tailings impoundments in Canada was undertaken for the NUTP (Golder Associates 1984 and Clifton Associates 1986).

The chemistry of tailings may have a significant effect on a liner. Saline solutions modify the grain structure in clays and increase permeability. This is true for bentonite clay-modified soils where sodium bentonite is added to reduce the soil permeability. Typically the clay grains shrink as sodium ions are displaced by divalent cations such as calcium. The effects are less pronounced when calcium bentonite is added. Recent testing of bentonite-modified soil liners has been reported (Wallace 1987, and Janardhanam and Perumal 1987).

If salt or acid concentrations are high, clays may also become dispersive and susceptible to cracking and piping, and exhibit higher permeabilities. Although this aspect is a consideration, no serious problems have been noted in any foundation, cutoff wall or till core at a tailings area in Canada.

Acid solutions affect a liner. Acid solutions are neutralized by the soil liner which dissolves the mineral grains. Conversely as the pH shift occurs several precipitation reactions occur. Dissolution may increase permeability, while precipitation may reduce permeability. Clogging is possible through calcite or gypsum precipitation the super saturated solutions or other sources of calcium or bicarbonate ions as that may be in groundwaters at the base of the pile. Where clay liners have been found to be more permeable than expected, based on the results of laboratory tests, it has often been found that leakage has occurred through fissures and construction defects, rather than by breakdown in the clay mineralogy (Daniel 1987). Most commonly used synthetic membrane materials are not likely to be affected by tailings solutions. The most effective seepage barriers are in situ natural materials such as till, bedrock and possibly even peat.

7.3.4.2 Design Concepts for Seepage Control

The principle design concepts for seepage control at Canadian Tailings sites have been described elsewhere (SRK 1986). The following is a summary:

a) Seepage Quantity

The quantity of flow, Q, carrying contaminants along a flow path can be determined from Darcy's Law.

$$Q = kiA$$

where:

k is the permeability of the porous medium in which flow is occurring,
i is the hydraulic gradient along the flow path, and
A is the area of the flow path.

To reduce the quantity of contaminated flow from an impoundment, any one, or a combination, of k, i, or A can be reduced, by installing appropriate design elements. It is often possible to achieve sufficient reduction in a single quantity to reduce Q to acceptably low values. An example is the installation of a synthetic liner with a sufficiently low k value. Often it is preferable, for either long-term security or economic considerations, to select a combination of design elements, which together provide the required reduction, possibly with some redundancy. Some of the alternative design concepts are mentioned below.

b) Reducing Permeability

(i) Liners

Liners can be one of a number of types:

- Natural geologic liners occur when the permeability of the foundation soils or rocks are sufficiently low that Q is reduced to an acceptable value. Generally mass permeability values of less than 1×10^{-8} m/s are required. Fractures in, and hetrogeneity of, the foundation soils are the main concerns.

- Clay or low permeability soil liners may be used to form a core in the embankment and to line the impoundment basin. Admixtures of bentonite or other low permeability, natural materials additives may also be considered. Permeability values of less than 1×10^{-9} m/s are required. Such liner materials must be checked to ensure that they are not degraded by the tailing materials.

- Flexible membrane liners

Membrane liners may be divided into two common types:

- flexible polymetric membranes, and
- spray applied asphaltic liners.

Both of these membrane types can be used to line impoundments of complex geometric shape. A review of liner types available in Canada, their characteristics and installation requirements has been undertaken (Firlotte and Gould 1984). They conclude that, of the membranes reviewed, high density polyethylene (HDPE), Hypalon (CSPE), and chlorinated polyethylene (CPE) all exhibit sufficiently good characteristics to warrant further study, as do catalytic airblown asphalt or asphaltic-elastomeric compounds. While the membrane materials have extremely low permeabilities (probably less than 1 x 10^{-13} m/s) the operative permeability, resulting from liner defects, which are typically used are 1 x 10^{-10} and 1 x 10^{-12} m/s respectively for asphaltic and polymeric liners.

It is questionable how well these assumed operating values reflect actual field installations, as testing procedures for large expanses of liners are unprecise. Such liners are very thin and the long-term degradation remains a prime concern, particularly in the chemical and radiation environments of some tailings solutions (Mitchell 1984), the harsh climatic conditions of northern Ontario and Saskatchewan, and when subjected to deformations associated with foundation settlements. Experience indicates that membrane liners can be a practical and effective solution in the short term. Long-term suitability remains to be demonstrated.

Membrane liners can be effectively combined with other liners such as clay liners or natural geologic liners. The second liner limits releases from membrane liners imperfections and remains as a durable long-term liner. This combination may be particularly effective where the contaminant concentration and, or the seepage driving forces reduce with time.

(ii) Reducing the Permeability of the Tailings

Tailings often are of relatively low permeability themselves, depending on their gradation and density. Thus the slimes zones may have very low permeabilities (1 x 10^{-10} m/s) while sand beach zones may have relatively high permeabilities (1 x 10^{-6} m/s). If segregation had been prevented a typical value might be 1 x 10^{-8} m/s, with a range of 1 x 10^{-9} to 1 x 10^{-6} m/s depending on the density. When tailings are discharged in a slurry they have a low density. Under load (of incumbent tailings or cover materials), and when drained, they consolidate to a denser state. Thus the permeability can reduce with time to levels which are typical of natural liner materials. The low permeability of the slimes zones and of densified tailings can be used to advantage for controlling seepage losses from the tailings impoundment in the long-term. It requires appropriate tailings deposition in a manner which achieves a partially saturated deposit as discussed in the next section. Air bubbles in the tailings pores impede seepage flow. Semi-dry layered tailings deposition minimizes vertical permeability, see Section 5.5.

c) Reducing the Hydraulic Gradient

The hydraulic gradient, i, is determined by the head loss, h, and the flow path length, L.

$$i = h/L$$

Reductions in i may be brought about by both a decrease in h or an increase in L. For a synthetic liner, L is usually very small, resulting in an extremely high value of i over the liner thickness. For natural geological liners L is considerably greater and for this reason lower values of k are acceptable for natural geologic liners than for synthetic membranes.

(i) Underdrains

The value of h applied to a liner can be drastically reduced by installing an underdrain above the liner. If water is drained away, the hydraulic head on, and consequently the seepage through, the liner may be small. Some design, construction and management considerations for the installation of underdrains are given elsewhere (van Zyl and Robertson 1980). The installation of underdrains also has the effect of increasing consolidation in the tailings pile and therefore decreasing its permeability and of reducing the total volume of water, and dissolved contaminants available for seepage. Methods for the analysis of drainage and consolidation in typical uranium tailings piles are described elsewhere (Fayer 1985). These techniques are all well suited to Canadian conditions.

(ii) Partially Saturated Layered Tailings

A partially saturated, low segregation, high density tailings deposit can be obtained by a combination of layered tailings placement and underdrainage. Air drying of the layers of tailings induces suction pressures in the tailings resulting in partial saturation, increased tailings densities and reduced permeabilities. If thickened tailings discharges are used to place uniform layers of tailings, the degree of tailings segregation can be minimized. The semi-dry or sub-aerial technique of tailings placement has been employed in other countries for many years (Robertson et al 1978). Because of the extreme climatic conditions in northern Saskatchewan and the limited evaporation, the potential benefits of this technique are considerably reduced. Concerns exist regarding the effects of ice lensing in the deposits. This technique has been used at Key Lake (Knight and Haile 1983). Operating experience is as yet limited. It is anticipated that a considerably reduced piezometric head will be imposed on the impoundment liner on abandonment.

(iii) "Dry" Tailings

By filtering the tailings in the mill, most of the tailings solution, and the dissolved contaminations can be removed, prior to placing the tailings in the impoundment. If the entry of additional surface water can be prevented, the free water that is available for seepage is small. This effectively reduces the head on any "liner" and the rate of contaminated seepage to the amount at which the residual water can drain from the tailings. In practice, some infiltration will occur at the tailings surface; the rate will depend on a variety of factors relating to the cover, surface drainage and weather. Placement of "dry" tailings also results in a non-segregated tailings of relatively high density and consequently relatively low permeability (Robertson et al 1982).

The filterability of tailings varies greatly, depending largely on the amount and nature of the clay fraction. Pre-conditioning of the tailings, by flocculants and other agents can considerably improve their amenability to filtration. Different filtration equipment, including belt filters, belt presses, filter presses, centrifuges and cyclones must be evaluated to establish the most suitable. Filter cakes of differing moisture contents will be obtained, and the cost of filtration can vary enormously for the different equipment types and tailings. The handleability, trafficability and stability of such "dry" tailings will vary according to the moisture content. These characteristics should be evaluated before selecting the filtering equipment, transportation and placement equipment or designing the impoundment management system. A successful "dry" uranium tailings system has been operated for a number of years, at the Miniere Dong - Trieu Mine in France. Dry tailings disposal is being tried and evaluated in the new in-pit tailings disposal system at Rabbit Lake Mine for the Collins Bay B-Zone orebody (Gulf Minerals Canada 1981).

(iv) Hydraulic Balancing

Hydraulic balancing is achieved by maintaining an essentially zero head difference between the piezometric head and in the surrounding receiving waters. Since there is no head difference, the hydraulic gradient is zero. No advective flow occurs and the only mechanism for contaminant migration is diffusion. This is achieved by placing tailings below water level in a natural or artificial lake. To prevent the pressure effects due to groundwater flux the tailings should be surrounded by an envelope of high permeability. This principle was initially recognized and proposed as a contaminant measure by Gulf Minerals Canada for the Rabbit Lake mine, Collins Bay B-Zone orebody tailings. Since flooding will only occur on impoundment decommissioning the results have yet to be demonstrated. Evaluation of contaminant migration from the uranium tailings at the Beaverlodge Mine (Eldorado Resources 1983), which were placed largely in Fookes Lake, suggests that it will be effective.

d) Reducing the Sectional Area of Flow

For a given tonnage of tailings, only three factors influence the seepage area: the geometry of the impoundment; the volume of water stored in the impoundment; and, the density of the tailings.

- Geometry of the tailings impoundment. Generally speaking, the greater the thickness of the tailings, the lower the area covered by tailings. Both the seepage area and the area of environmental impact are decreased.

- Volume of water stored. Tailings impoundments are often used to store excess process water. Minimizing the additional stored water, minimizes the volume of waste product in the tailings dam and consequently both the seepage area and hydraulic head.

- Increased density somewhat reduces the total volume of the tailings mass and hence the surface area A, as well as decreasing the permeability of the tailings and the total volume of solutions available for seepage. Tailings placement and management techniques which result in increased tailings density have multiple beneficial effects.

7.3.4.3 Evaluation of Stability Methodology for Liners

Seepage barriers can consist of natural geologic strata or engineered barriers comprised of natural materials or membranes. This evaluation considers only engineered natural material barriers, and manufactured membranes. Information on the liners is taken from two studies conducted for the NUTP; (Golder Associates 1984) on the evaluation of flexible membrane liners; and (Clifton Associates 1986) on evaluation of natural materials as seepage barriers.

a) Hazards to Liners

The liners must be stable against both chemical attack from leachate and reagents, and physical damage due to climatic or other factors. (Clifton Associates 1986) identified four generic stages of geochemical evolution of a leachate in the tailings pond. These stages included:

- the process control stage which lasts for the operating life of the pond,

- sulphide oxidation where sulphides are present, resulting in low pH and deposition of precipitates in pore spaces,

- resolution phase where precipitates are dissolved from pore spaces in the liner, and

- the long-term phase where minor solution of soil constituents takes place at about pH 5.

The liners must be stable against chemical attack by the leachate during any one of these stages. The liners should also be able to withstand accidental spills of process reagents and hydrocarbons and the effects of radiation. In addition, the liners must be able to resist physical damage including: puncture; cold temperature shrinkage an cracking; ultraviolet degradation; degradation due to radiation; freezing and thawing consolidation; piping; and, osmotic effects.

The stability of natural and manufactured membrane liners under these influences is discussed below.

b) Flexible Membranes

Golder Associates (1984) conducted a preliminary evaluation of nine polymeric and three asphalt liner types considered suitable for the physical and chemical environment in the uranium mining areas in Canada. All showed suitable chemical resistance, but all were subject to installation difficulties. Asphalt showed suitably low permeabilities but was judged to be difficult to construct uniformly and was susceptible to damage due to differential movement, equipment traffic and climatic effects such as freezing and thawing. Asphaltic membranes were judged to required a soil cover to provide adequate long-term stability.

The polymeric membranes were judged to have suitable chemical resistance but were very susceptible to physical damage during installation due to vehicular traffic or improper subgrade preparation. One of the most common defects was inadequate field seaming of the membrane. The major seepage loss through manufactured membranes was judged to be primarily through liner defects. A uniform high quality installation of a polymeric liner would provide a barrier with an effective permeability of 1×10^{-12} m/s. However, this number would be greatly increased with an increase in the number of physical defects. No information is provided on the durability and physical stability of these membranes when exposed to long-term uranium tailings seepage.

c) Natural Materials

Four natural materials were identified as potentially suitable seepage barriers. These included till, silt, peat and bentonite modified till. The chemical stability of each of these materials was examined for each of the four geochemical conditions. Detailed results appear in SRK (1986).

The anticipated long-term effects of uranium tailings leachate on the natural barriers is small. However, significant short-term effects could take place in sodium saturated clays, compacted wet of optimum moisture content with fresh water. Such clays are subject to ion replacement (calcium for sodium) with resulting shrinkage and increase in permeability. They are also subject to osmotic consolidation if the salt concentration in the leachate is substantially higher than that in the pore water. Osmotic consolidation will also cause shrinkage of the barrier leading to cracking and increased permeability.

In addition to the chemical durability, natural barriers must also exhibit stability under certain physical influences. The requirements for stability include:

- Adequate frost protection to prevent development of ice lenses in or under the liner. Such lensing could lead to differential heave, rupturing the liner during the freezing process, and thaw consolidation causing upward flow and release of pore water during the thawing process.

- An adequate factor of safety against piping. Since the liner may be subject to a high hydraulic gradient, the gradation of the liner and the parent material must obey accepted filter criteria. If it does not, fines may be eroded from the liner causing a rapid increase in permeability leading to uncontrollable releases.

d) Summary

Little is known about the long-term behaviour of manufactured flexible membranes. It is therefore difficult to evaluate their stability over the 100 to 10,000 year time frame. In the absence of such information, it must be assumed that these membranes will eventually degrade under the influence of chemical, physical or biological attack.

Uranium tailings leachates will affect the permeability of natural materials, but the overall effect is expected to be small. Considering the relatively inert nature of the natural materials, it is expected that they will remain chemically stable and intact as a barrier if protected against freezing damage and against piping.

e) Canadian Case Studies

Seepage rates were evaluated from the Stanleigh Mine Tailings Impoundment, (Golder Associates 1980). This site is typical of the Generic sites at Elliot Lake. This basin has a capacity for more than 60 million tons of tailings and is contained by three large perimeter dams. The remaining perimeters are bedrock hillsides typical of the rock-rimmed tailings repositories in this region. The seepage pathways from these basins are typically limited to the fault zones which are often coincident with the dam valleys. Under the closed-out conditions, the average flow through the basin would be approximately 195 L/s (MacLaren 1980). The seepage rate from the close-out facility was estimated (Golder Associates 1980) to be 3.7 L/s or less than 2% of the water leaving the basin. This is equivalent to a net infiltration rate of 29 mm over the 400 ha of tailings at close-out, or 3% of the annual precipitation falling directly onto the tailings surface.

A consolidated muskeg layer was proposed originally for the Key Lake tailings impoundment liner, (Knight and Piesold 1979). Experimental work demonstrated that the in situ consolidated peat had a permeability of 10^{-9} m/s. This is about 2 orders of magnitude lower than the glacial till deposits in the area. The facility was actually constructed with a bentonite modified glacial till with a permeability of 1 x 10^{-9} m/s. Estimated long-term seepage losses from the lined Key Lake tailings management area were between 10 and 80 m^3/d, (Knight and Piesold 1986). This is equivalent to between 12 and 100 mm of precipitation or 2.6 to 20% of the annual precipitation falling above the underseal area (30.4 ha).

The natural bedrock liner at Stanleigh is expected to function as well, or better, than the man-made liner at Key Lake.

7.3.5 NATURAL ATTENUATION BARRIERS

Seepage from a uranium tailings impoundment must pass through several engineered and natural materials before reaching potential receptors. These may include sand in the tailings underdrain, the clay/till liner materials, natural sands and tills and the shallow bedrock.

The transport of contaminants in seepage through engineered and natural barriers or modified soils depends on the permeability and attenuation characteristics of the materials. The extent to which each natural material acts as a geochemical trap to the water-borne transport of radioactive and non-radioactive contaminants is a function of the mineralogical composition of the material, the chemical composition of the tailings seepage, and the pH conditions that are established as the seepage penetrates the barrier material.

A number of mechanisms are responsible for contaminant retardation in soils including adsorption, coprecipitation, hydrous metal oxide complexation, organic matter complexation, colloid formation and microbial effects. Of the above mechanisms, adsorption or ion exchange on soil particles is generally regarded as one of the most important factors. Iron, manganese and aluminum oxides and hydroxides have also been found to be important geochemical traps in attenuating contaminant transport. Where significant pH shifts occur, precipitation reactions are often the primary attenuation mechanism.

7.3.5.1 Design Concepts for Attenuation Barriers

The design of attenuation barriers makes use of contaminant transport groundwater models. These models require a detailed knowledge of the groundwater regime and specific data on the partitioning coefficients for the elements to be modelled. The basic processes which affect subsurface transport are:

- advection (water flow)
- hydrodynamic dispersion (comprising mechanical dispersion and diffusion)
- retardation
- radioactive decay or in-growth

Advection is a process by which the constituent is transported by the bulk motion of the flowing groundwater. To calculate the affect of advection on contaminant concentration, the groundwater velocity (Darcy's velocity) must be determined:

$$v = ki$$

where:

v = Darcy's velocity
k = coefficients of permeability
i = hydraulic gradient

Mechanical dispersion is a spreading phenomenon caused entirely by the motion of the fluid. Mechanical dispersion may occur in the direction parallel to the bulk fluid flow (longitudinal dispersion) or in the two directions perpendicular to the flow (transverse and vertical dispersion). Since longitudinal dispersion is normally much stronger than transverse dispersion, the latter is often neglected (Freeze and Cherry 1979). To incorporate the longitudinal dispersion process, a dispersion coefficient is required;

$$D_l = \frac{dv}{n}$$

where:

D_l = longitudinal dispersion coefficient
d = dispersivity
n = porosity

where the rate of solute transport is shown, i.e., in low permeability environments it is controlled by diffusion. The diffusion process is defined by Fick's Law, where

$$\frac{\partial C_e}{\partial t} = D_e \frac{\partial^2 C_e}{\partial X^2}$$

Ce = solute concentration
t = time
X = distance of solute transport
D_e = effective diffusion coefficient

To account for the complex geochemical processes (including dissolution, adsorption and coprecipitation) which control radionuclide migration, a "bulk" retardation factor is used:

$$R = 1 + \frac{p_b}{n} K_d$$

where:

R = retardation factor
ρ_b = bulk density of the soil
K_d = distribution coefficient for the contaminant

The distribution coefficient K_D is predecented on the assumption that removal reactions are instantaneous and wholly reversible. In the case of radionuclide migration this term may be better thought of as a removal coefficient.

The radioactivity decay constant of each radionuclide is determined from the following equation:

$$\lambda = \ln(2)/t_{0.5}$$

where:

λ = radioactive decay constant
$t_{0.5}$ = radioactive half-life

The in-growth of a radioactive element may be expressed as:

$$A_d = A_p\,(1 - e^{-\lambda_d t})$$

where:

A_d = activity of the daughter in solution
A_p = activity of the parent in solution
λ_d = radioactive decay constant for the daughter
t = time

The one-dimensional movement of a nonreactive radionuclide or element in a saturated, homogeneous, isotropic semi-infinite column undergoing continuous radioactive decay can be described by the following partial differential equation:

$$\frac{\partial C}{\partial t} = \left(D\ell \frac{\partial^2 C}{\partial X^2}\right) - \left(\frac{q}{n} \frac{\partial C}{\partial X}\right) - (\lambda C)$$

where:

X = the distance from the tailings impoundment
t = the time
C = the activity of the i^{th} radionuclide or element

If the element is non radioactive, λ is set to zero.

Modifying the equation to include the retardation term previously described by the bulk retardation factor results in:

$$\frac{\partial C}{\partial t} = \left(\frac{D\ell}{R} \frac{\partial^2 C}{\partial X^2}\right) - \left(\frac{q}{nR} \frac{\partial C}{\partial X}\right) - (\lambda C)$$

This mass balance equation is the standard equation employed in all contaminant transport models.

Once measurements are available for seepage flow and quality, the K_D for the barrier and the mechanical dispersion coefficient, then the benefits of the attenuation barrier can be assessed.

7.3.5.2 Canadian Case Studies

Numerous studies have been conducted at uranium tailings sites to evaluate the migration of contaminants in seepages. Selected examples are reviewed below.

The migration of acid seepage for the non-operating Nordic Mine Tailings area in Elliot Lake has been evaluated elsewhere (Morin et al 1981).

The Nordic Tailings Area is on top of a sand aquifer which varies in thickness from 9 to 15 m. Water infiltrating the surface migrates vertically downward into the aquifer and passes laterally away from the site. As highly acidic seepages enter into and move through the sands, they are buffered and undergo substantial physico-chemical reactions. These reactions result in a marked reduction of the velocities of the radionuclide and the acidic water compared with the rate of seepage flow. In fact, Morin observed that the acid front velocity was approximately one percent of the seepage velocity.

Values are provided for partitioning coefficients which indicate radium levels are approximately 70 mL/g, uranium values between 2000 and 3000 mL/g. Morin et al suggest that these radionuclide migration rates are controlled by adsorption. They also found that lead and thorium were greatly retarded in the sand aquifer.

Assuming a K_D value of 70 mL/g for the sand, the retardation factor for radium would be approximately 400. Therefore radium moves at a rate of 1/400 of the groundwater flow. Therefore in 1000 years at a groundwater flow rate of 10 m/yr, the radium would have only travelled 25 m (ignoring dispersion). This work suggests that if thorium-230 is not present, that radium will decay before entering a surface water receptor if transport distances are more than 100 m.

Knight and Piesold (1986) undertook a preliminary evaluation of contaminant migration rates in the natural materials in the vicinity of the Key Lake tailings repository. This study reviewed partitioning coefficients for both radionuclides and metals, including arsenic and nickel. Testing was undertaken with tailing seepage on four local natural materials: a sand used in the underdrain system, a bentonite modified till; the local glacial till; and the Athabasca sandstone bedrock. The calculated retardation factors for each element and soil are summarized in Table 7.3-2.

TABLE 7.3-2
KEY LAKE STUDY 1986
MONITORING OF LAYERED URANIUM TAILINGS - PHASE II

Mean and Distribution of Retardation Factors

Formation	As	U	Ni	Mo	Zn	Th^{-230} Th^{-232}	Th^{-228}	Ra^{-226}
Filter Blanket	448 (224-895)	1	1 (122-730)	239	1 (6-98)	25 (35-74)	50 (20-45)	30
Underseal	235 (64-1901)	343 (74-642)	14 (1-33)	14 (7-26)	1654 (1268-1901)	58 (1-128)	45 (1-96)	824 (413-1901)
Till	322 (161-642)	147 (74-642)	1	35 (6-487)	118 (11-1167)	6 (1-11)	16 (1-50)	156 (25-312)
Athabasca Formation	1473 (737-2945)	415 (24-2301)	47 (1-231)	645 (323-1289)	576 (1-5751)	116 (1-346)	24 (1-70)	254 (116-461)

The major findings were that arsenic is very well retarded by natural soils and therefore is not expected to migrate substantially from the site. Nickel is poorly retarded in the tills and soils while similar divalent metals such as zinc were well retarded. Radium retardation factors were low in the sands but more typical of literature values in the other natural materials. Thorium retardation factors were very low in comparison with other results. This may in part be the result of the low initial concentrations of thorium or may also be due to the propensity of thorium to form very fine colloids which can show up as a soluble phase, (Melis 1986b).

A conceptual decommissioning plan for the Amok Phase II tailings repository was prepared (Meneley and Cherry 1986). This plan has exploited the subsurface natural materials as a long-term barrier to contaminant migration. In this plan, the infiltration of water into the surface zone will be minimized by fresh water diversion. However, all water that does infiltrate the site will travel vertically downward to the pervious underlying aquifer. At Nordic, (Morin et al 1981), the natural materials in this aquifer have a great capacity to retard radium migration. The primary natural materials are peat and glacial sands.

Modelling carried out by the University of Saskatchewan has shown that with the retardation that occurs, radium will undergo substantial radioactive decay reducing long-term levels of radium in the receiving waters to below drinking water standards.

In summary, the provision of tailings basins with pervious foundations has typically been frowned upon. Sites with liners or impervious bedrock foundations are promoted as providing superior containment. In Canada where there is substantial net infiltration into tailings areas, there may well be merit in developing basins which provide for long seepage pathways through natural foundation soils. This is often superior to the long-term surface discharge of contaminated waters from the decant or spillway of a tailings area.

7.4 BARRIERS TO RADON

7.4.1 INTRODUCTION

To reduce the flux of radon gas from a uranium mill tailings pile to those required by standards or design criteria, it is usually necessary to place a cover over the tailings. The cover therefore serves as both the infiltration barrier and the radon barrier. Different requirements govern design of the barrier for infiltration compared to radon control. Nevertheless by balancing the two requirements an economic design can be achieved, in most instances.

The current analytical and design technology for barriers to radon has been developed in the U.S.A. and is consequently geared toward the specific site and material conditions of uranium deposits in the southwest part of that country. These differ from sites in Canada in a number of key respects, the most important of which are the moisture and temperature regimes. The role played by water in suppressing radon emanation and its greater availability at Canadian sites reduces the magnitude of the problem here. However, some special problems for the long-term integrity of tailings covers may be posed by freezing of this water.

7.4.2 DESIGN CONCEPTS FOR RADON BARRIERS

The principal isotope of radon, ^{222}Rn, is the radioactive decay product, ^{226}Ra, which has a half-life of 3.82 days. The parent isotopes, ^{226}Ra and ^{230}Th, have half-lives of 1,600 and 77,000 years respectively, thereby assuring continued generation of radon for thousands of years. This makes the long-term design characteristics of radon barriers particularly important in tailings where the emanating fraction of radium is high. The radon produced at a tailings pile surface (and the potential hazard it poses) can be described by the flux which, for a bare, dry, homogeneous tailings pile is given by:

$$J_t = 10^4 \, RpE \quad \lambda D_t \tan\left(h \, \frac{\lambda X_t}{D_t}\right) \qquad (7.4.1)$$

where J_t = radon flux from the tailings surface (pCi m^{-2} s^{-1})

R = specific activity of radium in the soil (pCi g^{-1})
p = dry bulk density of the soil (g cm^{-3})
E = radon emanation coefficient (dimensionless)
λ = decay constant of radon (2.1×10^{-6} s^{-1})
D_t = diffusion coefficient for radon in the total pore space of the tailings (cm^2 s^{-1}).

The aim of the current radon barrier design technology described in this and in the following section is to reduce the flux to a specified amount by employing methods based on diffusion theory. In the U.S.A., this criterion for acceptability of radon flux is 20 pCi m^{-2} s^{-1}. Cover composition and thickness is designed to restrict radon diffusion long enough so that some of it decays to its solid daughter products before it exits from the cover. The parameter in equation 7.4-1 which describes this radon movement in the tailings themselves or any superimposed cover material in the diffusion coefficient.

7.4.2.1 Diffusion Coefficient

Values of the diffusion coefficient can be developed by direct laboratory measurement or, less accurately, by estimation. Measurable quantities in determining D_t are the radon flux and the radon concentration at specified positions in the tailings cover stratigraphy. These data can be collected in the laboratory or in the field.

The diffusion coefficient of a soil cover can be estimated by theoretical models of the soil pore structure and fluids and the exchange of radon which occurs between air and water in these interstices. The basic parameters required by such models are the moisture, compaction and pore size distribution, all of which can be measured or calculated. Alternatively, empirical correlations (Rogers et al 1984) can yield estimated values of D_t using the fraction of saturation, m, or the moisture content parameters, and porosity, p:

$$D_t = 0.07 \exp[-4(m - mp^2 + m^5)] \qquad (7.6\text{-}2)$$

This correlation equation is plotted in Figure 7.4-1, which also illustrates the important control which moisture exerts upon the diffusion coefficient. By reducing the interstitial volume of air through which radon is diffused and by absorption, high moisture contents effectively reduces surface radon flux. For this reason, water ponded upon tailings piles has been proposed as a viable radon barrier.

7.4.2.2 Bare Tailings Flux

Before the type and thickness of a candidate material for a radon barrier is developed, flux at the tailings surface must obviously be evaluated (equation 7.4-1). Sample radon exhalation measurements from four representative Canadian tailings areas are shown in Tables 7.4-1, -2, -3, along with descriptions of the tailings surface conditions at the time of sampling. The data from the Key Lake, Saskatchewan tailings area are included as representative measurements over tailings derived from high-grade ores, while the remainder are typical of low to medium-grade ores. It can be seen that fluxes over wet or frozen tailings surfaces are considerably lower than over dry surfaces. These differences reflect the attenuating property of relatively high ice or water contents.

It has also been shown that bare tailings flux is virtually independent of tailings thickness at common diffusion coefficients because of radon decay within the tailings themselves, see Figure 7.4-2. The surface flux is a measure of the emanating power of the uppermost tailings layers and it is therefore advantageous from the radon barrier design perspective, to minimize the surface area of tailings in favour of increasing their thickness.

7.4.2.3 Radon Barrier Types

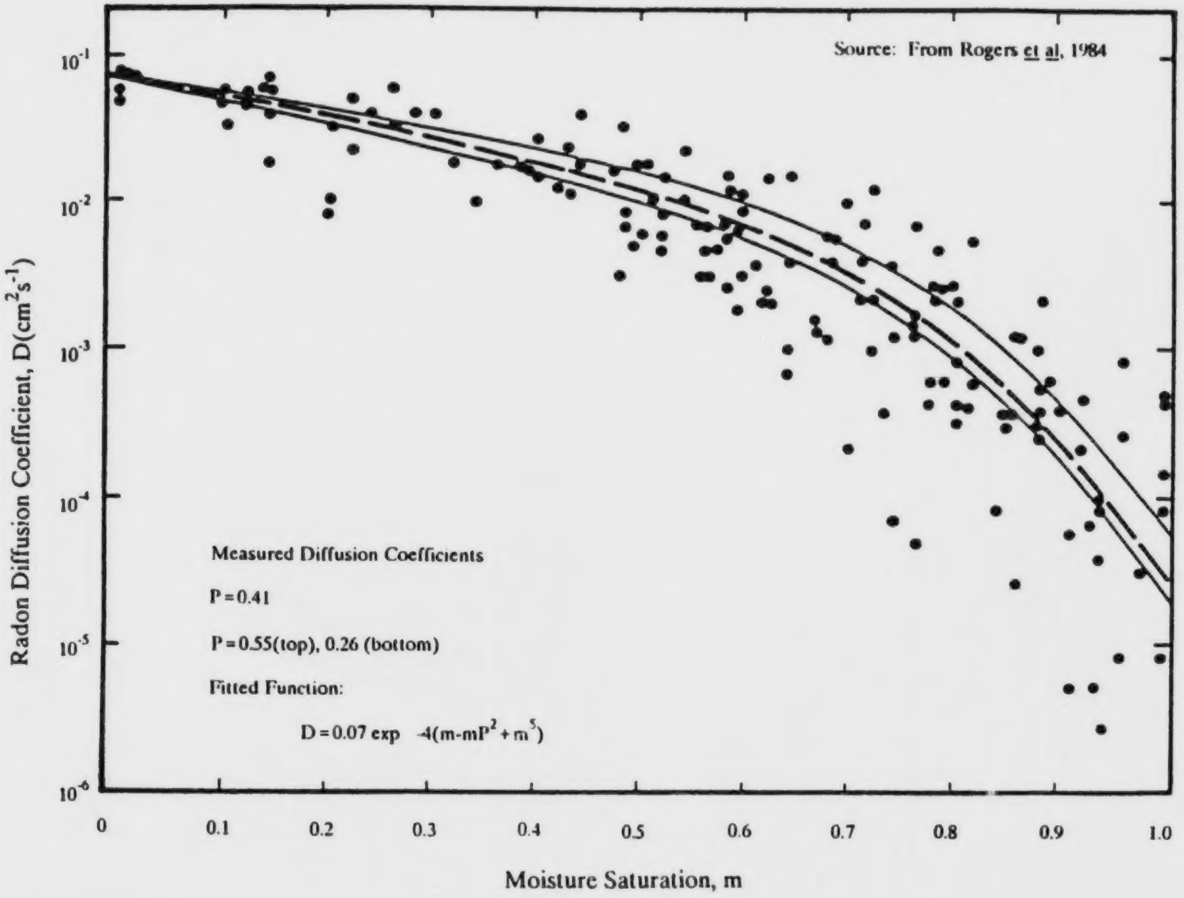
A range of natural materials or combinations of material can be employed as radon barriers. These include single or multiple soil overburden layers, waste rock, and low-grade tailings in a variety of stratigraphic sequences. High compaction and full saturation should be sought for any porous medium cover to minimize the pore space available for diffusion. For this reason, waste rock or rip-rap is a poor radon inhibitor. Also, vegetation by itself has been shown to be inadequate as a radon barrier, (DSMA, Atcon 1985).

A number of constraints dictate the selection of an appropriate cover. These are economics, the availability of materials, the types and thickness of cover being considered to control infiltration or surface erosion, and the flux criterion above the cover. It has been suggested that for low or medium grade ore tailings in Canada, minimal barriers, i.e. vegetation or thin soil cover, may be adequate given the remoteness of the tailings areas and their generally high moisture content (Steffen Robertson and Kirsten 1986a). The high-grade ores from the Saskatchewan deposits may require thick (up to 3m) soil or water covers to attenuate radon flux satisfactorily.

The development of frost is both advantageous and problematic in radon barrier design. By reducing available pore space, frost development reduces radon diffusion through porous media. Depending upon moisture content, radon exhalation rates from bare, frozen tailings are reduced by factors of more than 300 compared to unfrozen tailings (Golder et al 1986). This can have a significant impact on barrier design in the Canadian tailings areas, where it is climatically possible to maintain high moisture levels in the tailings pile.

However, frost can disrupt the surface through heaving. Over many years, biennial freeze-thaw cycles can produce surface fissures and cracks which may decrease the attenuating capacity of the surface cover, though the consequences for other aspects of cover design, such as infiltration and surface erosion, are more serious.

The possibility of employing a free water cover as a radon barrier has not been widely explored in the literature, though its potential has been recognized in reports on two Saskatchewan tailings sites:



Source: From Rogers et al, 1984

Figure 7.4-1 Comparison of Measured Radon Diffusion Coefficients with a Simple Correlation Function Assuming Different Porosities

TABLE 7.4-1

SUMMARY OF RADON EXHALATION MEASUREMENTS AT BEAVERLODGE (SASKATCHEWAN) AND NORDIC (ELLIOT LAKE) TAILINGS SITES

Beaverlodge Tailings Site

Date	Exhalation Rate (Bq/m2/s)	Surface Condition
85.08.10	3.2	Dry
85.08.10	0.8	Wet
85.08.10	0.9	Wet
85.08.13	0.5	Damp
85.08.13	3.3	Damp
85.08.13	13.5	Damp
85.08.19	0.3	Damp
85.08.11	3.4	Dry
85.08.11	3.9	Dry
85.08.11	2.6	Wet, grass cover
85.08.20	4.7	Dry
85.08.19	0.9	Damp
85.12.16	1.4	Frozen
85.12.16	0.1	Frozen
85.12.15	0.004	Frozen
85.12.17	0.85	Frozen

x = 2.52
s = 3.29
Max = 13.5
Min = 0.1

Nordic Tailings Site

Date	Exhalation Rate (Bq/m2/s)	Surface Condition
84.06.21	4.3	Bare tailings
84.06.22	4.6	Bare tailings
84.06.23	3.0	Bare tailings
84.06.24	7.7	Bare tailings
84.06.25	11.2	Bare tailings
84.06.26	6.7	Bare tailings
84.07.17	6.3	Bare tailings
84.07.17	2.6	Vegetated
84.07.20	0.6	Vegetated
84.07.20	1.0	Bare tailings
84.07.22	0.5	Vegetated
84.07.22	2.3	Bare tailings
84.08.14	1.5	Vegetated
84.08.14	6.8	Vegetated
84.08.15	4.0	Bare tailings
84.08.15	1.1	Vegetated
84.08.18	3.7	Bare tailings
84.08.19	5.7	Bare tailings
84.08.19	10.8	Bare tailings
84.08.20	3.1	Bare tailings
84.08.20	3.0	Vegetated
84.08.22	6.2	Bare tailings
84.09.24	1.6	Vegetated
84.09.24	0.4	Bare tailings
84.09.25	8.1	Bare tailings
84.09.25	2.1	Vegetated
84.09.25	0.1	Vegetated
84.09.25	1.0	Bare tailings
84.09.26	2.1	Bare tailings
84.09.26	2.2	Vegetated
84.09.27	0.5	Vegetated
84.09.27	1.8	Vegetated

x = 3.64
s = 2.99
Max = 10.8
Min = 0.1

TABLE 7.4-2

COMPARATIVE SUMMARY OF WINTER AND SUMMER RADON EXHALATION MEASUREMENTS AT LACNOR (ELLIOT LAKE) TAILINGS SITES

	Exhalation Rate ($Bq/m^2/s$)			Surface Condition	
Date	Winter	Summer	Ratio: Winter/ Summer	Winter	Summer
85.03.07/85.06.14	0.253	0.19	1.332	Damp, soft, swamp muck	Damp, no vegetation
85.03.07/85.06.14	0.046	0.307	0.150	Frozen surface	Vegetated surface
85.03.07/85.06.14	0.028	1.1	0.025	Frozen surface	Vegetated surface
85.03.07/85.06.14	1.52	0.988	1.538	Frozen surface	Vegetated surface
85.03.07/85.06.13	0.011	0.776*	0.014	Dry	Moss and grass cover
85.03.07/85.06.13	0.043	0.56*	0.077	Frozen, dry	Dry
85.03.06/85.05.27	0.378	0.544	0.695	Frozen, dry	Dry
85.03.06/85.05.27	0.29	0.198*	1.465	Damp, soft, under ice	Damp
85.03.06/85.05.27	0.715	0.257	2.782	Frozen	
85.03.06	0.007			On surface of ice	
	0.0185			Ice removed	
85.03.06	0.104			No ice	
85.05.27		0.075			Covered 25 mm water
85.05.27		0.114			Saturated
85.03.07/85.06.13	0.288	0.171	1.684	Damp	Moist, no vegetation
85.03.07/85.06.12	0.009	0.841	0.011	Dry, hard, sandy	Damp, no vegetation
85.06.12		1.93			Damp
85.03.07/85.06.12	0.19	6.67	0.028	Soft, mushy	Damp, no vegetation
85.03.07/85.06.12	0.258	1.45	0.178	Frozen, dry	Damp, no vegetation
85.03.07/85.06.12	0.252	0.836	0.301	Frozen, dry	Dry, moss covered
85.06.26		4.96			Vegetated, dry
85.06.26		0.951			Vegetated, dry
85.06.14		0.013			Surface saturated
85.07.12		1.7			Sparce grass cover
85.07.12		0.566			Dead grass removed
85.07.12		0.668			Sprigs of grass
85.07.12		1.58			Dry, moss covered
85.07.12		0.578			Dry, bare surface
Number	17	25	14		
Average	0.259	1.121	0.734		
Std. Dev.	0.362	1.496	0.843		
Maximum	1.52	6.67	2.782		
Minimum	0.007	0.013	0.011		

* Denotes average of 2 samples

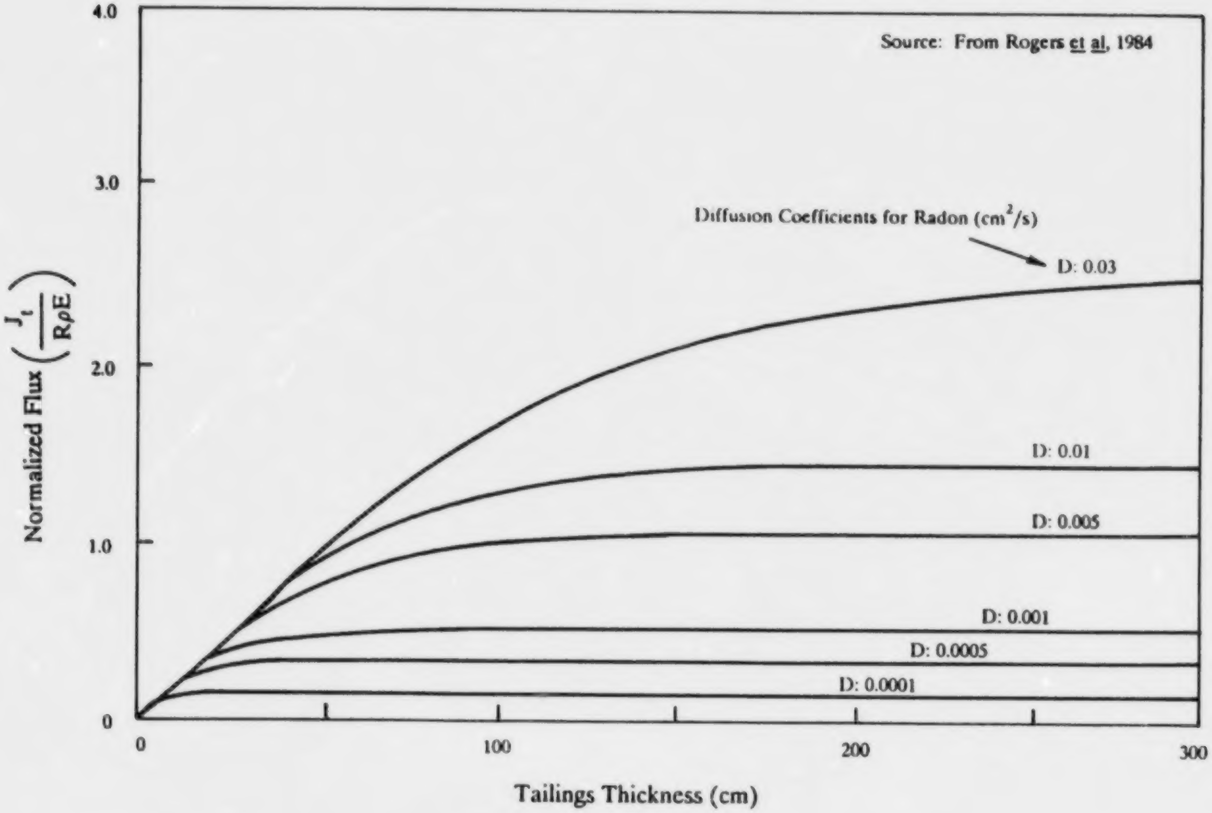
TABLE 7.4-3

SUMMARY OF RADON EXHALATION MEASUREMENTS AT KEY LAKE TAILINGS SITES

Date	Winter/ Summer	Exhalation Rate ($Bq/m^2/s$)	Surface Condition
84.09.13	s	0.88	Very wet tails
84.09.13	s	0.78	Very wet tails
84.11.20	W	0.007	On surface of ice (150 mm) above tails
84.11.22	W	0.14	On surface of ice (150 mm) above tails
85.05.31	s	10.2	Dry and cracked
85.07.11	s	3.9	Dry and cracked, old tails (Oct '84)
85.08.27	s	7.3	
85.09.29	W	2.4	Surface thawed
85.10.26	W	64.3*	Surface frozen
85.02.14	W	0.026	On surface of snow
85.02.15	W	0.03	On surface of snow
85.07.12	s	1.8	Dry winter tails
84.09.13	s	1.11	On dry tails
84.09.15	s	2.15	On dry tails

Average Summer	3.51
Average Winter	0.43
Ratio Winter/Summer	0.12

* not included in computations of averages



Source: From Rogers et al, 1984

Figure 7.4-2 Normalized Flux From Bare Tailings as a Function of Tailings Thickness and Diffusion Coefficient

Beaverlodge and Rabbit Lake. Estimates of radon releases to the atmosphere by diffusion from tailings porewater through a 200 mm deep water cover would be negligible. Greater depth up to 2 m may be warranted, however, to suppress release through turbulent mixing of the cover water by surface winds. These may be cautious estimates, given that water covers over inactive tailings would probably be frozen for large parts of the year at both Ontario and Saskatchewan sites.

7.4.2.4 Cover Thickness Calculation

The technology currently employed in the U.S.A. to develop the thickness of soil overburden radon-attenuating tailings covers is exemplified by the mathematical computer model RAECOM (Rogers et al 1984), a flow chart for which is shown in Figure 7.4-3. The model calculates radon fluxes through a two-phase multilayer system of porous media, representing the tailings pile and its cover. Fluxes for cover thicknesses are calculated by iteration until levels which satisfy a specified criterion are reached.

The model calculations are based on one-dimensional steady-state radon diffusion through the cover layers. Seven layer-specific input parameters are required:

- thickness of layer,
- dry bulk density of soil,
- porosity,
- moisture content,
- emanating fraction of radon,
- radon diffusion coefficient, and
- radium concentration.

Figure 7.4-4 illustrates the effects of soil cover thickness and diffusion coefficient on the surface radon flux for seven separate cases of a single soil layer overlying bare tailings. These curves were calculated using a two-region tailings and cover diffusion equation included in the RAECOM model, with input parameters taken from U.S. data.

The same equation has been employed to produce two examples of single-layer covers for Canadian tailings, as shown in Figure 7.4-5. Values for the input parameters have been drawn from compilation of the physical and radiological properties of the Lacnor Elliot Lake and Key Lake tailings, and local unconsolidated deposits which could be used as cover material. The base tailings surface fluxes to be attenuated by these example barriers are the averages of the measured summer exhalation values listed in Table 7.4.1. The cover thickness calculations were aimed at completely suppressing the surface flux, and the resulting thicknesses should be viewed as cautious estimates, given the lower average surface flux during the winter months due to higher moisture content and frost development within the tailings as well as the probable attenuation due to frost development within the cover itself. Moreover, higher compaction, resulting in lower porosity than that used in the calculations, could probably be achieved during cover application. Such reduced porosity usually results in greater moisture retention, depending on the grain size distribution of the cover material, and also serves to lower the diffusion coefficient. A thinner cover with these characteristics could thereby produce a reduced surface flux.

The moisture content of the Lacnor tailings shown in Figure 7.4-5 was assumed to be the same as measured values of 15% from the tailings. Measurements from the active Key Lake tailings beaches range between 100% and 200% moisture which, over the long-term, are unlikely to be maintained. Tailings in the near-surface zone dessicate and crack, and moisture levels tend to drop well below full saturation. Because of the nature of the precipitates a substantial amount of chemically bound water will be retained. Without specific information on the near-surface moisture contents a conservative value of 20% as measured in local till deposits, was therefore used in the calculations for the barrier material.

Source: From Rogers et al, 1984

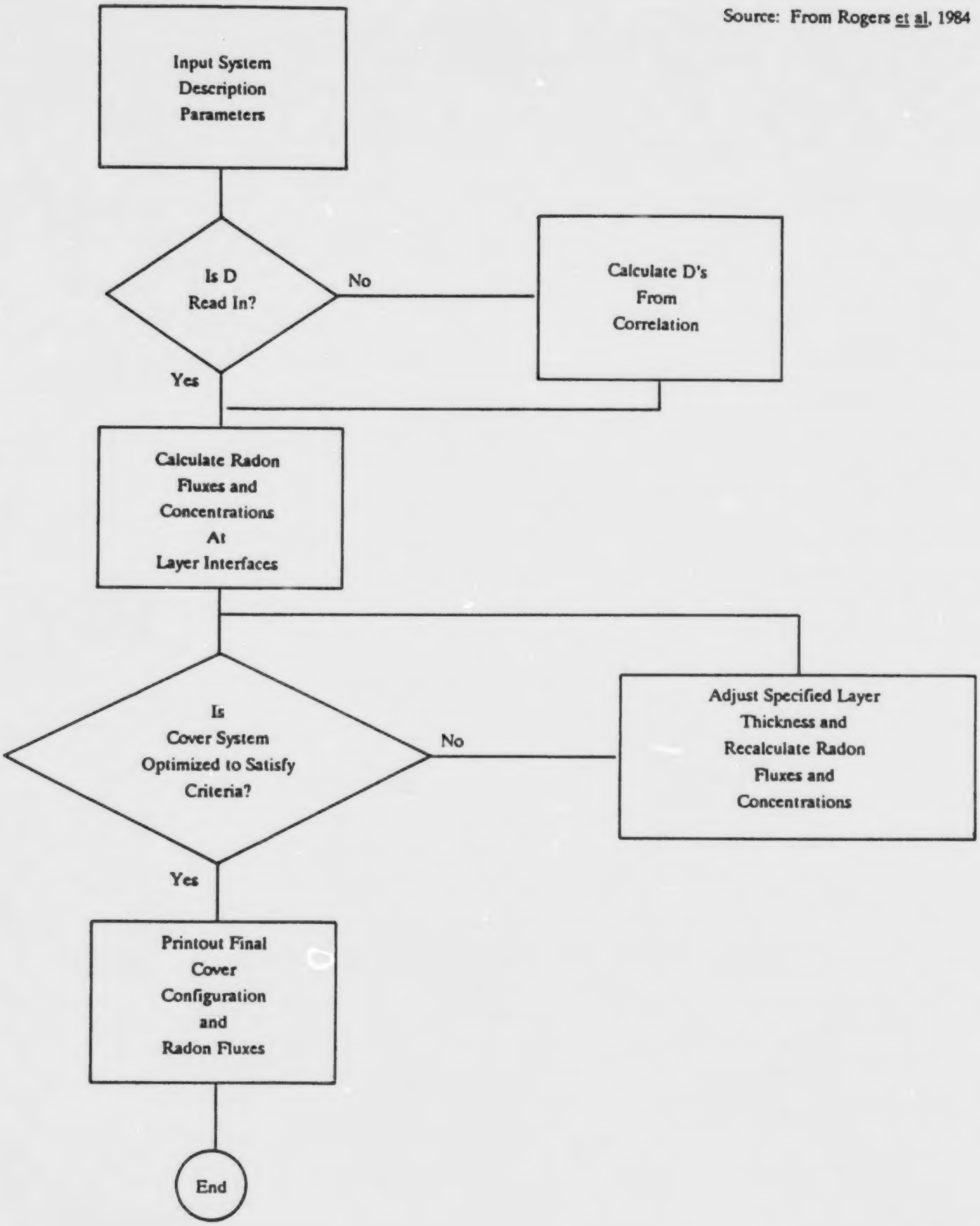

Input System Description Parameters
Is D Read In?
No
Calculate D's From Correlation
Yes
Calculate Radon Fluxes and Concentrations At Layer Interfaces
Is Cover System Optimized to Satisfy Criteria?
No
Adjust Specified Layer Thickness and Recalculate Radon Fluxes and Concentrations
Yes
Printout Final Cover Configuration and Radon Fluxes
End

Figure 7.4-3 Major Components of the RAECOM Model (U.S.A.)

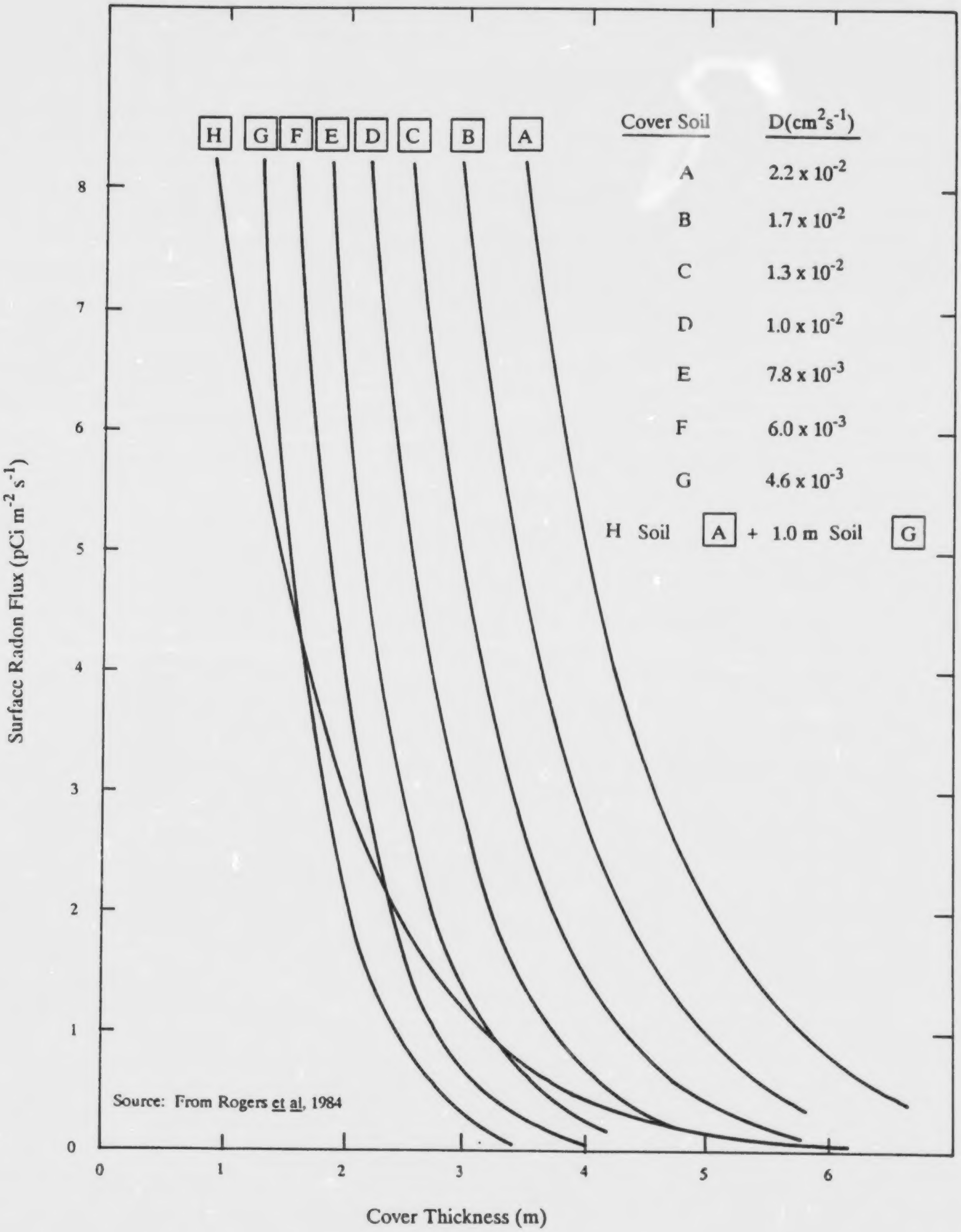
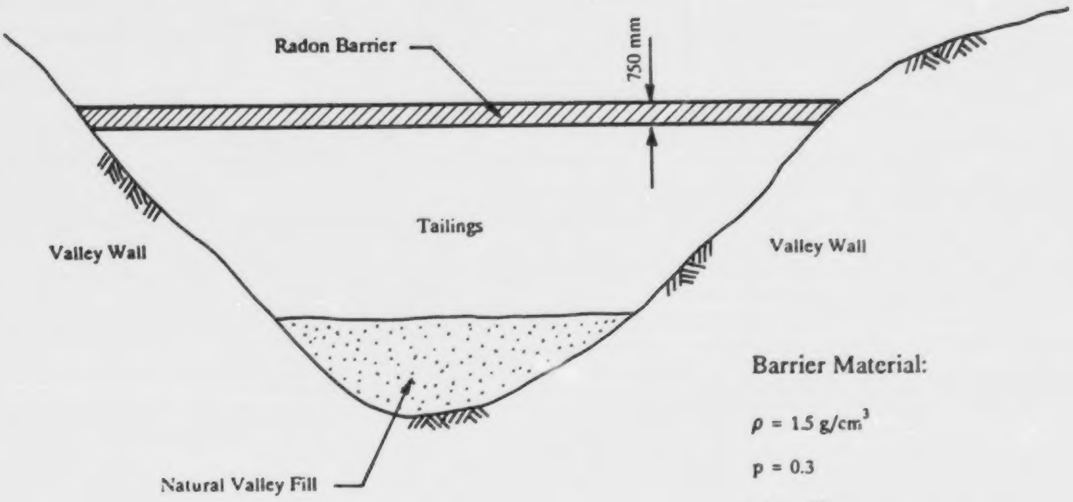


Figure 7.4-4 Effect of Soil Thickness on Surface Radon Flux


Radon Barrier
750 mm
Tailings
Valley Wall
Valley Wall
Natural Valley Fill

Barrier Material:

ρ = 1.5 g/cm^3

p = 0.3

M = 15%

g = 2.67

D = 0.003 cm^2/s

A) Lacnor Tailings Area

Barrier Material:

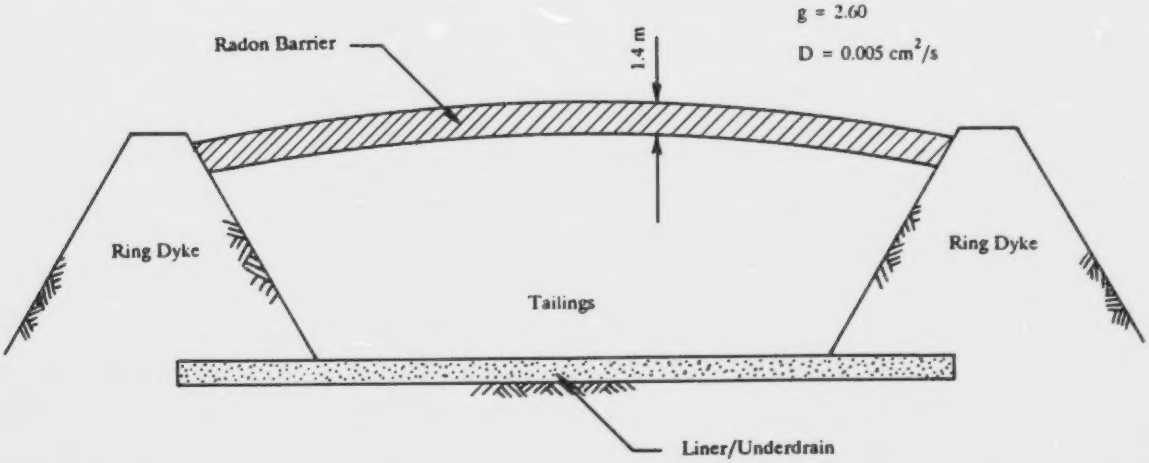
ρ = 1.5 g/cm^3

p = 0.3

M = 20%

g = 2.60

D = 0.005 cm^2/s


Radon Barrier
1.4 m
Ring Dyke
Ring Dyke
Tailings
Liner/Underdrain

B) Key Lake Tailings Area

Figure 7.4-5 Examples of a Single-Layer Radon Barrier

7.4.3 LONG-TERM INTEGRITY OF RADON BARRIERS

The considerations for ensuring long-term stability of a radon barrier generally coincide in principle with methods employed to minimize surface erosion. Of particular importance, however, is the estimation of equilibrium moisture content of the cover materials.

A recommended method of computer modelling of this parameter is set out in DOE Technical Approach Documents, although its applicability to Canadian uranium tailings characteristics and climate is uncertain, especially with regard to the long-term effects of freeze-thaw cycles. While maintenance of high moisture levels are desirable and more likely to be achieved at Canadian tailings sites, the geotechnical properties of cover materials, especially their susceptibility to cryogenic processes, require separate attention.

7.4.4 SYNTHETIC RADON BARRIERS

Some information on the effectiveness and potential use of various synthetic liners or covers is available in the literature. Asphalt has been proposed in the past for its initially low permeability and concomitant low diffusion coefficient. However, it readily forms cracks due to both dessication and freeze-thaw and is also susceptible to disruption through differential settling. It does not, therefore, appear to be a suitable alternative for long-term applications.

Membrane materials, notably aluminized mylar in sheet form and a polysulfide copolymer compound in liquid form, have been shown to be capable of reducing radon emersion concentrations by greater than 95%, based on laboratory and in-situ tests on mine bulkheads (Archibald 1984). However, these barrier types are limited by the lack of data on their potential application to tailings piles and their long-term durability. Given the general objective to minimize the maintenance requirements of containment systems following close-out, the use of membranes as viable alternatives to barriers composed of natural materials remains to be demonstrated.

7.4.5 ATTENUATION OF DIRECT GAMMA RADIATION

Direct gamma radiation from the surface of a tailings area is a potential exposure pathway to man. Gamma radiation is readily attenuated by materials such as soil, water, concrete and various metals which have been employed in many shielding applications. The shielding value is for the most part simply a function of the density and thickness of the cover.

The most common shielding materials applied to the surface of a tailings area are waste rock and soil. The thickness of a typical soil or waste rock layer that will reduce surface gamma levels to one-half their original value is approximately 100 mm. Therefore, an estimate can be made of the approximate surface gamma levels for various cover depths where:

$$\text{Gamma Radiation Level with Cover} = \text{Initial Level}(0.5)^{x}$$

Where x = cover depth in mm/100

For example, to reduce the surface gamma levels from 60 μSv/hr to 2.5 μSv/hr a cover depth of 460 mm is required.

7.5 INTERCEPTION AND TREATMENT OF WASTEWATER AND OTHER WASTES

7.5.1 SOURCES OF WASTEWATER

The primary sources of wastewater from uranium mines are:

- minewater from underground operations and open pits,
- runoff from stockpiles,
- mill bleed and excess mill solution,
- tailings effluent, and
- seepage streams and underdrains
- millsite runoff (Key Lake)

The quantity and nature of these streams is highly site-specific.

During operation minewaters normally constitute a major flow component to the overall water balance. Minewaters are normally pumped to the mill where they are used in part as mill feed water. In some cases minewaters contain elevated levels of uranium and this would be precipitated for recovery in the mill. Excess minewaters would be pumped to tailings or sent to the mill wastewater treatment circuit.

Many mining operations have stockpiles of waste rock, low grade ore, ore blending pads and special wastes. Where runoff is contaminated, these waters are intercepted and sent during operations either to the mill or tailings basin.

Milling operations have very complex water balances with a high degree of internal water recycle. Fresh water uses are minimized by using various wastewater sources including minewaters, stockpile runoff and in some cases tailings effluents. There are many constraints on mill water quality which are process specific. For example, minewater may be acceptable for grinding makeup but may be too contaminated for use in the flocculant or gland water circuit. Older operations used to send all milling solutions to the tailings basin. In recent years, with the development of the higher grade ore bodies, mills have been only sending a thickened slurry to the tailings basin and treating the excess solutions at the mill.

Tailings effluents have characteristics similar to the alkaline mill solutions discharged to the basin. The quantity of flow will depend upon the slurry concentration in the mill tailings discharge, the amount of water retained in the settled solids as well as the quantity of other inflows such as precipitation minewater, etc. that are collected in the basin.

Seepage and underdrain flows are highly dependent on the tailings management practice and the site conditions. In places where underdrains are employed, the underdrain may be the major discharge flow from the tailings area.

The characteristics of these wastewaters are very site-specific and too broad to tabulate as typical levels. However, many of the contaminants in each of the streams are common, and the treatment technology for removal of the contaminants is common to all sources. The principal contaminants of concern in the wastewaters from uranium mines in Canada are:

- radium,
- arsenic,
- nickel,
- thorium,
- miscellaneous metals,
- ammonia, and
- soluble salts.

7.5.2 TREATMENT TECHNOLOGIES

7.5.2.1 Radium

The common technologies for radium removal include ion exchange, coprecipitation with barium sulphate, lime neutralization, filtration and reverse osmosis. The first three processes are technologies applied at uranium mines, while the latter three have been directed at removing radium from municipal water supplies.

Radium concentrations in effluents are highly variable and not necessarily related to the ore grade milled. Table 7.5-1 summarizes the radium effluent quality from selected tailings area discharges. Values range from <10 Bq/L to more than 100 Bq/L.

Ion exchange is the most recent process to be applied at a Canadian uranium mine. The full-scale treatment plant at Key Lake using a Dow Radium Selective Ion Exchanges is described elsewhere, (Neven 1985). This plant is treating low radium activity waters typically less than 3.7 pCi/L at a treatment efficiency of 90-95 percent. Under recent operating conditions, the first stage radium removal process using barium chloride addition with bulk precipitation and settling in a clarifier reduces radium levels to below regulatory limits without ion exchange. It appears that ion exchange is highly efficient and cost effective for the treatment of low radium concentrations.

TABLE 7.5-1
RADIUM LEVELS IN TAILINGS EFFLUENTS

Mine	Typical Ore Grade % U_3O_8	Radium Level pCi/L
Beaverlodge, Saskatchewan	0.25	2-4
Denison, Ontario	0.08-0.09	11
Key Lake, Saskatchewan	2.5	50-150
Quirke, Ontario	0.1	30
Rabbit Lake, Saskatchewan	0.37	40-50

Coprecipitation of radium with barium as a $Ba(Ra)SO_4$ precipitate has been the standard treatment technology applied at all uranium mines. Because the precipitate is very fine, coagulants and filtration may be required to reduce radium to levels acceptable for discharge. Barium chloride is received as a crystalline powder. It is made into a solution 10% to 20% by weight with fresh water. Because the solution is fed by metering pumps or gravity bleed systems, care must be taken to ensure low sulphate waters are employed for make up. Otherwise, barium sulphate precipitate will form and can plug lines and voids within the transfer systems. The addition of 10 to 100 mg/L of barium chloride is commonly employed. Coprecipitation is still the most favoured method for radium removal, especially where radium concentrations are high.

Both ion exchange and coprecipitation with filtration (or other solids removal techniques) can produce effluents that meet a total radium concentration of 0.37 Bq/L.

7.5.2.2 Arsenic

The standard procedure for arsenic removal is coprecipitation with iron and calcium. These precipitates can be removed in traditional clarifiers or settling ponds. Calcium arsenates are metastable at neutral pH, as are many other metaloarsenates such as ferric arsenate. Stability tends to improve as the iron to arsenic ratio increases. For efficient removal, iron to arsenic ratios in the order of 4:1 are typically applied. Levels of <0.5 mg/L can be achieved.

7.5.2.3 Nickel

The common treatment technology for nickel removal is lime precipitation at a pH of 9.0. Nickel hydroxide and possibly nickel sulphate precipitate, and may be redissolved if the pH is lowered into the neutral or acid range. Nickel can be typically reduced to <0.5 mg/L with lime precipitation.

7.5.2.4 Thorium

Thorium is a sparingly soluble element at pH ranges above 4.0. Therefore thorium is not normally at elevated concentrations in tailings area discharges. Simple lime precipitation to pH 5 to 7 will reduce thorium levels to substantially less than 1 mg/L. Thorium-230 activities in treated discharges in the neutral to alkaline range are typically <1 Bq/L.

7.5.2.5 Miscellaneous Metals

There are several metals in uranium mill tailings including rare earths, molybdenum, cobalt, vanadium, lead, copper and zinc. For all metals excepting molybdenum, simple lime precipitation to pH 8 to 9 is an adequate treatment method. Molybdenum removal is more complex and is usually carried out by co-precipitation with iron at pH levels of 4 to 5. Sludges are unstable at neutral to alkaline pH levels. Levels of 1 mg/L are the practical limit of this treatment technology.

7.5.2.6 Ammonia

Ammonia is a commonly used reagent for uranium precipitation. Ammonia is also present in tailings from the use of ammonium nitrate based explosives. Ammonia is a short term problem for which there is no readily adaptable removal technology for use in tailings effluents.

7.5.2.7 Soluble Salts

The most common salts in tailings effluents are calcium sulfate and sodium chloride. These chemicals are from reagents introduced in the milling process. Natural salts may also dissolve from the processed ore. Values for calcium sulphate are typically at saturation (~2200 mg/L) while sodium chloride levels are highly dependent upon the addition rate of sodium chlorate as an oxidizing agent in leaching. Typical sodium chloride levels range from 200 to 2000 mg/L.

There are no practical treatment technologies for reducing the salt content of tailings solution.

7.5.2.8 Acid Neutralization

Two materials are traditionally used for acid neutralization, lime and limestone. In the remote mining areas of northern Saskatchewan, long transportation distances make the use of limestone uneconomical. Both lime and limestone are typically fed as slurries with feed rates controlled by automatic pH control systems. Lime demands vary greatly and depend for the most part on the acid requirements for leaching and stripping. Reagent demands for tailings neutralization at low-grade operations, such as found in the Elliot Lake area, would be in the range of 18 Kg/tonne for limestone and 11 Kg/tonne for lime. At the high-grade operations would be in the range of 130 Kg/tonne of lime

(Senes 1986). Final pH levels in the neutralized tailings discharge for Elliot Lake mines are typically in the 9-10 range, while the high-grade operations discharge pH levels may exceed 11.0.

7.5.3 EXAMPLES OF CANADIAN PRACTICE

This section refers to flowsheets for water management and effluent treatment at four mining operations in Canada: Panel Mine in Elliot Lake, Stanleigh Mine in Elliot Lake, Key Lake Mine in Saskatchewan and the Collins "B" Mine in Saskatchewan. These mills cover a broad range of practice at Canadian mines.

7.5.3.1 Panel Mine

The Panel Mine is a 3000 t/day low-grade uranium mine in Elliot Lake. The water management flowsheet is shown on Figure 7.5-1.

The underground mine produces a large flow of water (approx. 25 L/s) from water use underground for drills and dust suppression. This minewater is highly acidic and contains elevated levels of uranium, iron, heavy metals, ammonium nitrate (explosives usage) and sulfates. Minewater is pumped to mill for uranium recovery and use in the circuit as grinding water and washing solution (etc.).

Tailings are neutralized with limestone and lime to pH of 9 to 11 and pumped with all excess mill and minewater solutions to the tailings pond. In the tailings pond, solutions are diluted with runoff and the pH is lowered by acid generation, ammonia oxidation and CO_2 dissolution. The tailings discharge is neutral to acidic and is treated with lime to adjust the pH for metals removals and barium chloride for radium precipitation. The precipitates are settled in two lined ponds in series. High quality effluents below effluent standards have been consistently achieved as shown in Table 7.5-2.

TABLE 7.5-2
PANEL MINE WASTEWATER CHARACTERISTICS

	Typical Levels (1986)			
	Minewater	Mill Tailings	Final Effluent	Effluent Standards Discharge
pH (units)	2.8	8.3	8.1	6.5-10.6
Ra-226 dissolved pCi/L	3.3	35	0.17	0.37
total pCi/L	-	-	0.34	-
As mg/L	<0.1	<0.1	<0.1	0.5
Ni mg/L	0.6	0.03	0.03	0.5
Uranium mg/L	55	1	0.2	<1

7.5.3.2 Stanleigh Mine

The Stanleigh milling operation in Elliot Lake is similar to Panel with a production rate of 5000 t/day.

The primary difference in wastewater characteristics is that the mine does not produce acid water. Neutralized tailings along with all excess solutions are pumped to tailings. The water management flowsheet indicated on Figure 7.5-2.

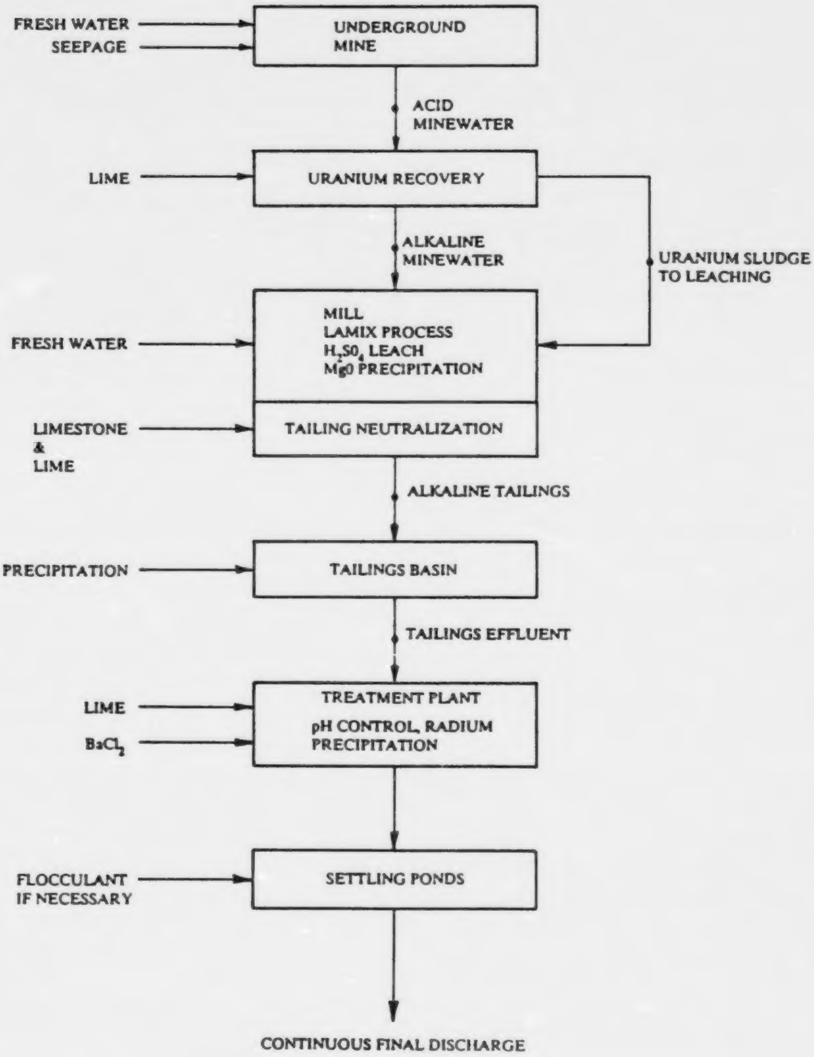

FRESH WATER
SEEPAGE
UNDERGROUND MINE
ACID MINEWATER
LIME
URANIUM RECOVERY
ALKALINE MINEWATER
URANIUM SLUDGE TO LEACHING
FRESH WATER
MILL
LAMIX PROCESS
H2SO4 LEACH
MgO PRECIPITATION
LIMESTONE & LIME
TAILING NEUTRALIZATION
ALKALINE TAILINGS
PRECIPITATION
TAILINGS BASIN
TAILINGS EFFLUENT
LIME
BaCl2
TREATMENT PLANT
pH CONTROL, RADIUM PRECIPITATION
FLOCCULANT IF NECESSARY
SETTLING PONDS
CONTINUOUS FINAL DISCHARGE

Figure 7.5-1 Panel Mine - Water Management Flowsheet

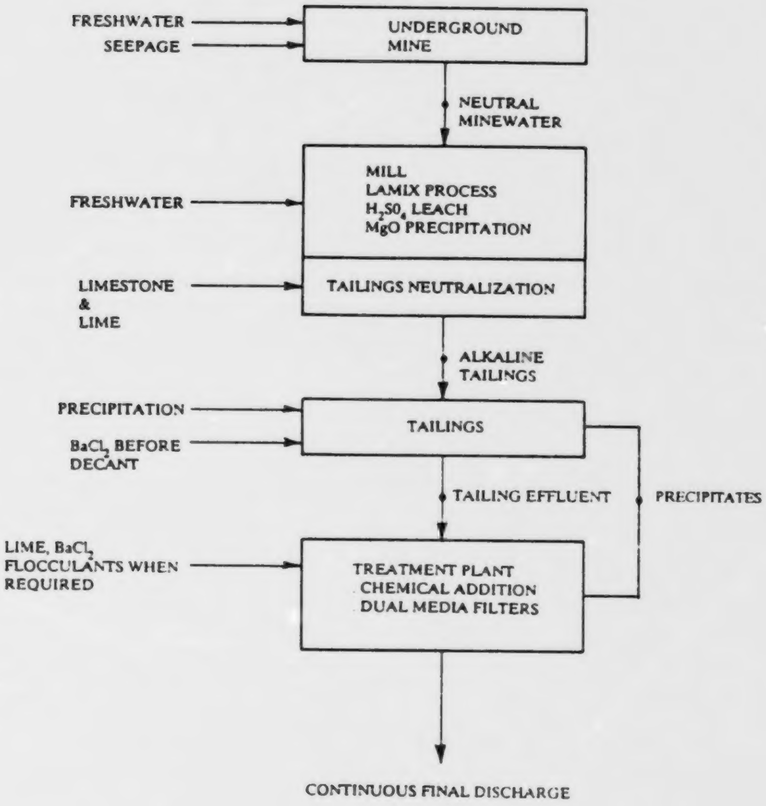

FRESHWATER
SEEPAGE
UNDERGROUND MINE
NEUTRAL MINEWATER
FRESHWATER
MILL
LAMIX PROCESS
H_2SO_4 LEACH
MgO PRECIPITATION
LIMESTONE & LIME
TAILINGS NEUTRALIZATION
ALKALINE TAILINGS
PRECIPITATION
$BaCl_2$ BEFORE DECANT
TAILINGS
TAILING EFFLUENT
PRECIPITATES
LIME, $BaCl_2$, FLOCCULANTS WHEN REQUIRED
TREATMENT PLANT
CHEMICAL ADDITION
DUAL MEDIA FILTERS
CONTINUOUS FINAL DISCHARGE

Figure 7.5-2 Stanleigh Mine - Water Management Flowsheet

The effluent treatment requirements at Stanleigh are the same as for Panel. Lime, if necessary, is added for pH control and 15 to 25 mg/L of $BaCl_2$ is added for radium precipitation. The major difference is that Stanleigh employs dual media filters to remove suspended radium instead of settling ponds. Effluent quality from the treatment plant is similar to Panel with total radium levels consistently <0.37 pCi/L.

7.5.3.3 Key Lake

Key Lake is a high grade (~2.5% U_30_8) open pit uranium mine operating at a milling rate of approximately 700 t/day. The water management flowsheet is shown in Figure 7.5-3. Water management is much more complex than for the Elliot Lake operations.

Mill process water is provided by stockpile runoff, minewater and fresh water where necessary. Excess minewaters can be pumped to either the bulk neutralization circuit or a ion exchange system if only radium removal is required.

All wastewaters are treated at the mill. These sources include tailings supernatent, tailings underdrainage and mill raffinate. The mill raffinates are precipitated with lime in a staged fashion and the precipitates settled in a thickener. The gypsum precipitate at pH of 7 contains high levels of arsenic, nickel and heavy metals and is pumped with tailings to the tailings area for disposal. Radium is also reduced during this precipitation stage.

The second stage precipitation involves a staged barium chloride addition and lime addition, to pH of 11 to precipitate radium and residual arsenic and nickel. Barium chloride rates are typically 100-150 mg/L of water treated. The precipitates are settled in a thickener. Originally, the thickener overflow was to be filtered, however, with internal sludge recycle, suspended solids removal has been excellent with very high sludge densities in the underflows from both thickeners. Therefore filtering is not necessary. All effluents are discharged to monitoring ponds where they are sampled before discharge. The characteristics of the major wastewater systems are shown in Table 7.5-3.

TABLE 7.5-3
KEY LAKE MINE - WASTEWATER CHARACTERISTICS

	Raffinate	Minewater	Typical Levels Tailings Seepage	Effluent Criteria
pH (units)	1			
As mg/L	2700	0.07	0.55	0.5
Ni mg/L	3300	12	0.09	0.5
Radium-226				
- Dissolved Bq/L				0.37
- Total Bq/L				0.37

7.5.3.4 Collins "B" Mine

Collins "B" is a medium grade (0.6% U_30_8) open pit uranium mine operating at a milling rate of 2000 t/day. The deposit is mineralogically similar to Key Lake with elevated levels of nickel and arsenic.

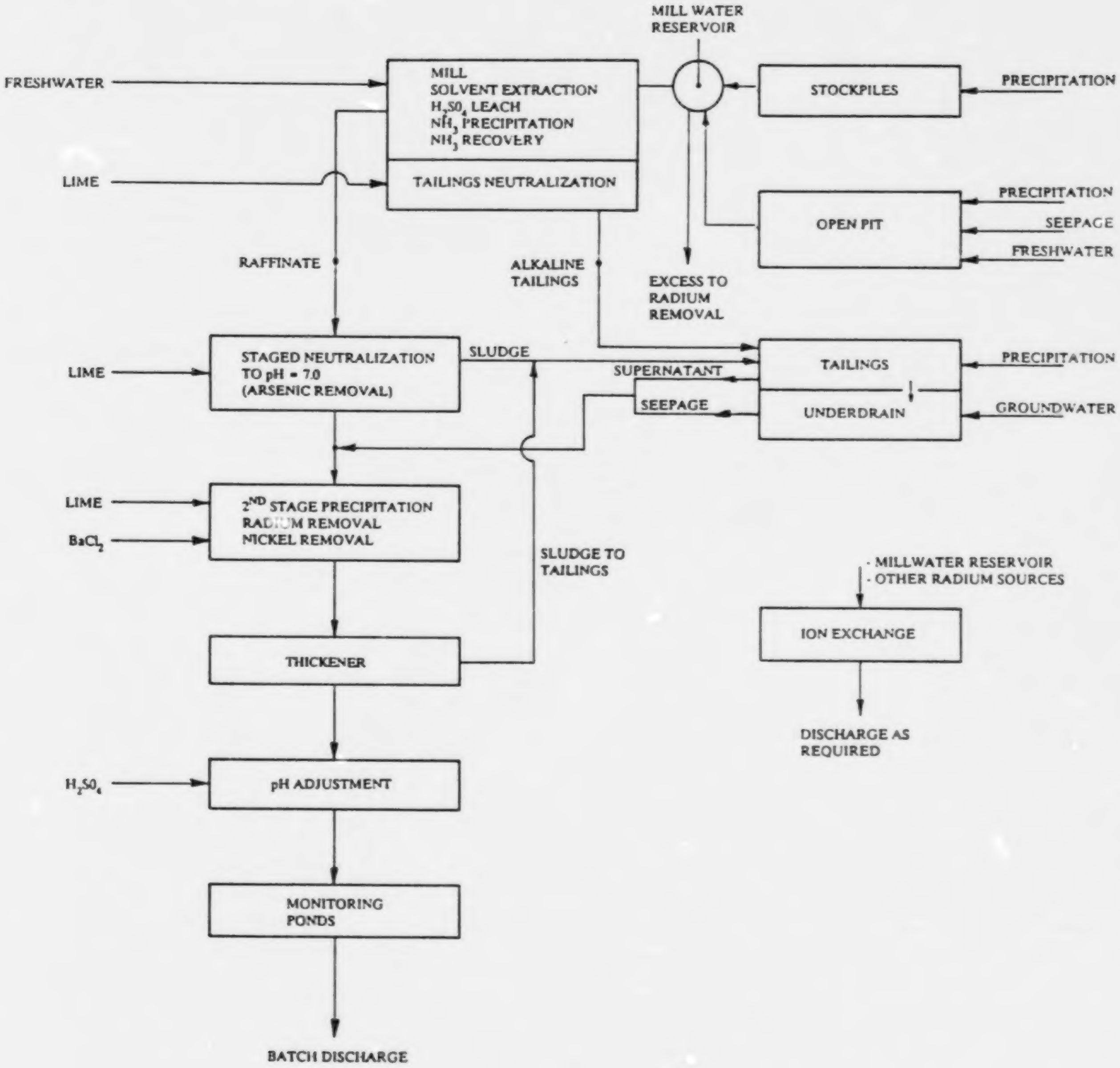

MILL WATER RESERVOIR
FRESHWATER
MILL
SOLVENT EXTRACTION
H2SO4 LEACH
NH3 PRECIPITATION
NH3 RECOVERY
STOCKPILES
PRECIPITATION
LIME
TAILINGS NEUTRALIZATION
PRECIPITATION
OPEN PIT
SEEPAGE
FRESHWATER
RAFFINATE
ALKALINE TAILINGS
EXCESS TO RADIUM REMOVAL
LIME
STAGED NEUTRALIZATION TO pH = 7.0 (ARSENIC REMOVAL)
SLUDGE
SUPERNATANT
TAILINGS
PRECIPITATION
SEEPAGE
UNDERDRAIN
GROUNDWATER
LIME
BaCl2
2ND STAGE PRECIPITATION
RADIUM REMOVAL
NICKEL REMOVAL
SLUDGE TO TAILINGS
- MILLWATER RESERVOIR
- OTHER RADIUM SOURCES
ION EXCHANGE
DISCHARGE AS REQUIRED
THICKENER
H2SO4
pH ADJUSTMENT
MONITORING PONDS
BATCH DISCHARGE

Figure 7.5-3 Key Lake - Water Management Flowsheet

The principal water sources to the mill are minewater, stockpile runoff and fresh water. The tailings and neutralized barren are sent to a filter plant, where water contents are reduced before combination and disposal in the mined-out Rabbit Lake open pit.

Wastewaters including barren solution, filtrate from the barren/tailings filter building, excess minewater and stockpile runoff and tailings underdrainage system are treated in the mill in a staged neutralization circuit where iron salts are added for arsenic precipitation, barium chloride for radium removal and lime for pH adjustment. The neutralized solution is sent to a thickener. The underflow is pumped to the filter plant and the overflow is pumped to the effluent polishing system. The polishing system includes two settling ponds where iron salts, barium chloride and lime can be added if necessary followed by sand filters. Effluents before filtration are meeting radium discharge objectives.

The water management flowsheet is shown on Figure 7.5-4.

7.5.4 OTHER WASTES

There are a number of wastes that may be produced at a uranium mining operation which require management either during the operation or at closeout. These wastes include:

- radium sludges from barium chloride treatment,
- metal hydroxide sludges from acid generating tailings,
- waste rock, mineralized waste, low grade ores, and
- garbage and other wastes.

The technology appropriate to the management of these other wastes is reviewed below:

7.5.4.1 Radium Sludges

The most common method of radium removal is coprecipitation with barium sulphate. The resultant sludge may contain a high level of radioactivity in comparison with the activity of the tailings. This depends upon the radium activity of the solution, the applied dosage of barium chloride and whether or not pH adjustment is also practiced. When lime is added in combination with barium chloride other metal hydroxides such as aluminum, magnesium, iron, etc. may also precipitate thus reducing the specific activity of the bulk precipitate. For a typical tailings effluent with 20 Bq/L of radium-226 and a barium chloride dosage of 25 mg/L, the resultant sludge would have a radium activity of approximately 700 Bq/g of dry sludge. If the radium precipitation was combined with pH adjustment, the activity could be greatly reduced.

Radium sludges can be highly variable in terms of their chemical make up and densities. Radium is often precipitated with many other compounds such as ferric hydroxide and gypsum. Densities of sludges can range from a few percent solids by weight (in settling ponds) to as high as 15 to 25 percent solids in mechanical thickeners (Neven et al 1985).

Only one management option has been practiced in Canada, that being disposal in the tailings basin. Sludges from treatment systems employing filtration plants or thickeners are normally continuously deposited with the tailings, while sludges stored in ponds are disposed of intermittently as required. Studies have shown that radium in the barium sulphate sludge was less soluble than the radium contained in the tailings (Huck et al 1982). In fact, radium could actually be absorbed by sludges disposed with tailings. Leaching rates for radium sludges increased under anoxic conditions when organics are present (Huck 1985). Huck therefore recommends that sludges be disposed of within oxidizing zones of the tailings area where organics are not present.

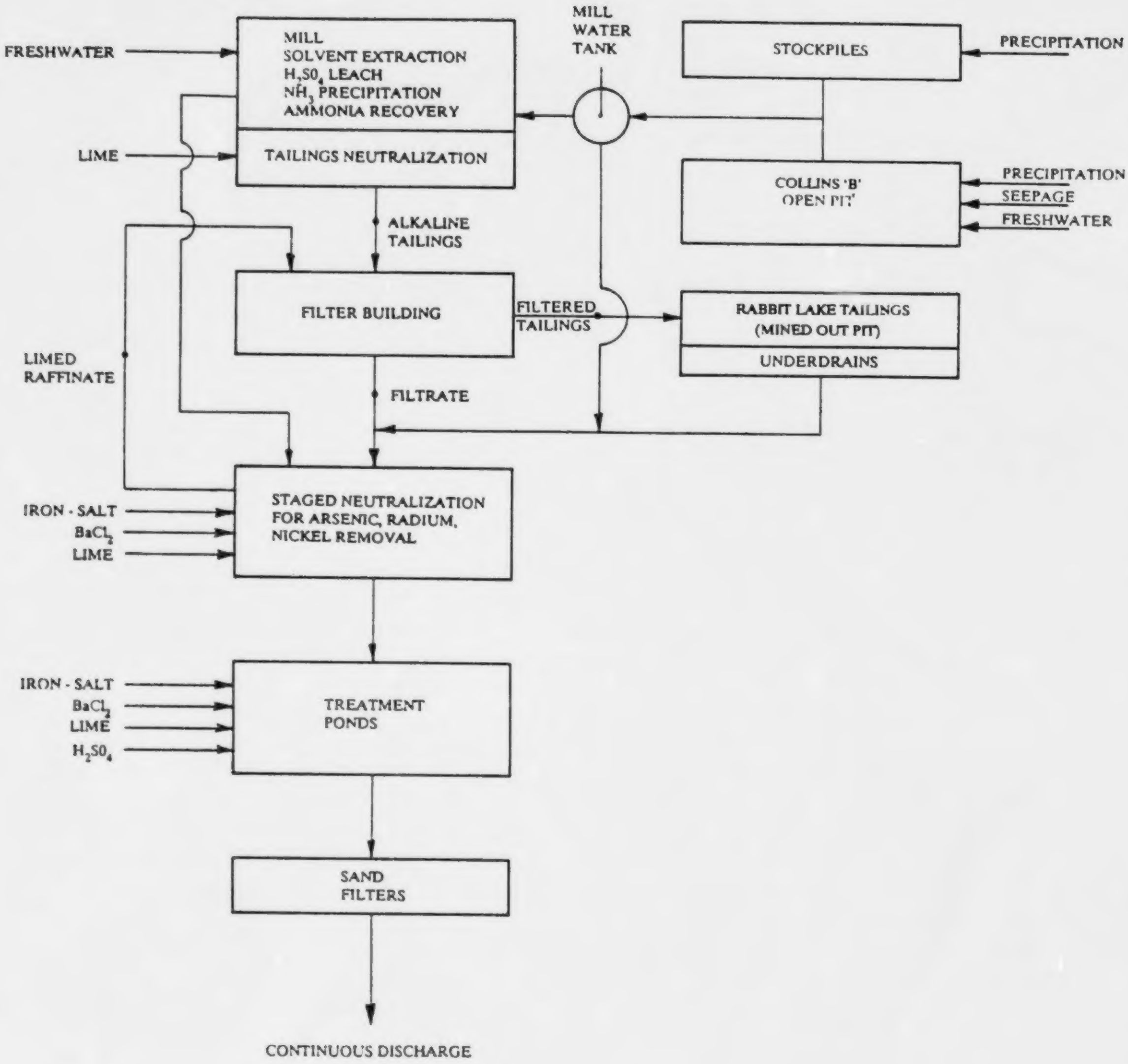

MILL
WATER
TANK
FRESHWATER
MILL
SOLVENT EXTRACTION
H_2SO_4 LEACH
NH_3 PRECIPITATION
AMMONIA RECOVERY
STOCKPILES
PRECIPITATION
LIME
TAILINGS NEUTRALIZATION
COLLINS 'B'
OPEN PIT
PRECIPITATION
SEEPAGE
FRESHWATER
ALKALINE
TAILINGS
FILTER BUILDING
FILTERED
TAILINGS
RABBIT LAKE TAILINGS
(MINED OUT PIT)
UNDERDRAINS
LIMED
RAFFINATE
FILTRATE
IRON - SALT
$BaCl_2$
LIME
STAGED NEUTRALIZATION
FOR ARSENIC, RADIUM,
NICKEL REMOVAL
IRON - SALT
$BaCl_2$
LIME
H_2SO_4
TREATMENT
PONDS
SAND
FILTERS
CONTINUOUS DISCHARGE

Figure 7.5-4 Collins 'B' - Water Management Flowsheet

7.5.4.2 Metal Hydroxide Sludges

The management of metal hydroxide sludges is a common problem for all tailings that are acid generators. Metal hydroxide sludges are gelatinous, poorly consolidated, have high water contents and occupy large volumes in any disposal area. Therefore the management of these sludges can be a major long-term concern.

The magnitude of the potential problem is best described by example.

Acid generating tailings such as exist in Elliot Lake contain 5-10% pyrite which can be oxidized to sulphuric acid. This oxidation produces very high concentrations of dissolved iron, sulphates and metals such as aluminum, magnesium, manganese and heavy metals. After neutralization with lime the metals precipitate principally as metal hydroxides and sulphate is precipitated as gypsum. Sludges typically would settle at dry densities of 0.01 to 0.1 t/m^3 (1 to 10 percent solids). A typical tailings basin would have a water table 1 to 2 metres below surface and all pyrite in this zone would be expected to oxidize. Therefore, if we assume a dry density of 1.3 t/m^3, 7.5% pyrite, and a 1.5 m unsaturated zone each square metre of tailings area would contain 0.15 t/m^2 FeS_2. After oxidation and neutralization with lime, 0.15 t/m^2 FeS_2 would produce 0.13 t/m^2 $Fe(OH)_3$ and 0.34 t/m^2 $CaSO_4$ for a total sludge production of 0.47 t/m^2. At a maximum probable density of 0.1 t/m^3, each square metre of tailings surface could produce 4.7 m^3 of sludge. Alternatively for each cubic metre of tailings oxidized, 3.1 m^3 of sludge are produced.

The disposal of this potentially vast quantity of sludge is a major concern to the industry.

The only practice employed for acid sludge disposal at uranium mines is disposal in the tailings area. This is a rational method but as noted in Section 1.2, the incorporation of precipitates with tailings does reduce the dry bulk density of the tailings. Moreover, if the tailings area becomes highly acidic, the residues will redissolve.

A study by the U.S. Bureau of Mines (Ackman 1982) on disposal practice for acid mine drainage sludges found that of 33 plants surveyed, 14 disposed sludges in underground mines, 9 permanently stored sludges in ponds, 9 hauled sludge to a coal refuse disposal site and 1 buried sludges on site.

For the Canadian situation, deep mine disposal is practical where truly abandoned workings are located. Disposed within the tailings basin is practical if adequate basin capacity exists. Because of the low permeability and poor dewatering characteristics of these sludges, they may well serve as an oxygen barrier over acid generating tailings. These sludges could be applied to the surface and covered with sand or waste to ensure the sludges retain a high water content. This may well provide the long-term oxygen barrier required to prohibit further acid production.

7.5.4.3 Waste Rock, Mineralized Waste and Low-Grade Ore

The problems associated with these wastes are highly site-specific and a function of the mining method and mineralogy and leaching characteristics of the waste.

With underground mining operations, waste production rates are generally quite low. Waste that is produced can generally be accommodated in the tailings basin. Often, waste rock can be disposed in mined out stopes. This is especially the case for operations that undertake development work in ore thus minimizing waste rock production.

Open pit mines typically produce massive quantities of barren waste rock. This waste is stockpiled as near as possible to the pit to minimize transportation costs. The waste is in many instances of minor environmental consequence. In selected cases low levels of contamination may occur in the rock which are leachable. Experience has indicated the most mobile of the radionuclides from waste rock dumps are uranium and to a lesser extent, radium. In Saskatchewan, barren waste has typically been defined as waste rock with 0.03% U_30_8 (Key Lake 1979).

Mineralized waste contains higher than background levels of contaminants including radionuclides and other metals and sulphides which may be amenable to leaching. These waste materials are generally stockpiled on lined pads with drainage control when not disposed in a tailings basin. Mineralized waste rock may also be acid generating. Mineralized waste is generally defined as waste rock with uranium contents of between 0.03% U_30_8 and the economic cutoff grade for milling.

Low-grade ore and special wastes contain adequate levels of uranium which may justify future processing. The low grade ore may either be blended with higher grade zones or milled during the later stages of operation. Special wastes can include mineralogically different zones which may require minor milling alterations to permit uranium recovery. Both these materials would be stockpiled on a lined pad with drainage controls. If not remilled, it is likely these stockpiles would have to be relocated to the open pit or tailings area. If reclaimed in place, consideration would have to be given to minimizing infiltration and seepage losses (where appropriate). In practice this is not easily accomplished.

As noted previously the waste management practices for each waste type are highly site specific and need to be thoroughly reviewed. The lessons learned from existing Canadian sites indicate:

- waste rock and mineralized waste can contribute significant contaminants loadings to receiving waters, and

- waste sites not properly located and managed are potential long-term concerns and possible can result in very high costs for reclamation.

Therefore it is essential that waste rock management practices be well thought out and designed prior to mining. Data should be collected on the mineralogy of the waste and the leaching characteristics and management plans developed to minimize long-term effects and reduce potential reclamation liabilities. Often extensive effort is placed with the management of a small volume of tailings while minimal effort is directed towards the management of massive quantities of waste. As a result, waste rock may potentially present a greater environmental concern.

7.5.4.4 Garbage and Miscellaneous Wastes

There are many sources of waste which require disposal. The sources include routine garbage (paper products, kitchen wastes, etc.), empty and damaged barrels, waste oils, off specification reagents (flocculants, solvents, etc.), demolition rubble, old machinery, mine timbers and cable, etc. These wastes can be classified into one of four categories - clean solid waste, contaminated solid waste, hazardous waste and liquid industrial wastes.

Clean solid wastes with characteristics similar to common domestic and commercial garbage, can be disposed in any approved landfill site. These sites are normally approved by a Provincial agency. In selected cases, garbage may be disposed within the tailings basin or waste rock dump. However, the recent trend is to a separate landfill site.

Contaminated solid wastes would include mill building wastes, laboratory wastes, mine timbers, non-salvageable contaminated equipment, mill demolition rubble, etc. These wastes, which contain elevated levels of radioactivity or other chemicals, would have to be disposed in a secure area to ensure no intrusion by people who could scavenge the wastes. This would normally be achieved by disposal within a controlled area on the mining site (typically the tailings basin or waste rock dump). Care must be taken to ensure flotable materials such as timbers are not disposed in the tailings in a location where they could be floated and lodged into decants or overflow spillways.

Hazardous wastes such as transformer oils, spent reagents such as solvents, and waste oils require specific disposal approval from the Provincial environmental agency. Onsite management of waste oils as fuel or dust suppresants is normally acceptable, flammable solvents could possibly be burned, and specific wastes such as old transformer oils with PCBs may require onsite storage or disposal by a licenced hazardous waste disposal contractor.

Most liquid industrial wastes are normally combined with tailings and disposed in the tailings area. These wastes include cleaning solutions, oily water, chemical spillages, etc.

CHAPTER 8.0
LONG-TERM CONTROLS FOR ABANDONMENT

Uranium tailings impoundments differ from other impoundments only in their requirements for long-term isolation and stability. Thus the primary objective of impoundment technology is to achieve stability in both the short and long-term.

8.1 DISRUPTIVE FORCES

Uranium tailings impoundments can fail under the action of the following disruptive forces:

- short-duration intense or extreme events such as floods, forest fires, earthquakes, and possibly volcanic action and glaciation, even deliberate sabotage, which apply forces exceeding the values for which the impoundments were originally designed, and
- slow but perpetual actions of wind and water erosion, frost action, weathering and decomposition of materials, and possibly biological action such as intrusion by roots, animals and man.

In all likelihood eventual failure of impoundment structures will result from a combination of short-term extreme events and a gradual wearing down. Structures cannot be expected to last for ever. But they can be designed and built to last for at least 200 years with reasonable assurance, and quite probably for an order of magnitude longer. Thus eventual collapse of these impoundment would not be deemed to be failures in the sense of unacceptable rates of release of radionuclides to the environment.

The major mechanisms of instability at Canadian sites are believed to be:

- chemical action on impoundment materials and drains,
- erosion of control structures, diversions and covers, and
- frost action on covers, diversions and drains.

Uranium tailings sites in Canada are generally within forested regions and fires are to be excepted, possibly many, although at irregular time intervals. The likely effect on impoundments will be erosion caused by temporary loss of the protective forest cover. The risks need better assessment, since the effects may be severe.

Mechanisms of degradation are discussed in detail in later sections of this chapter, but the disruptive forces that bring about this degradation are summarized below. Both short-term extreme events as well as the gradual forces of nature, are considered in some detail elsewhere (SRK 1986). Briefly the forces to be considered are either climatic or geotectonic.

8.1.1 WEATHER AND CLIMATIC EFFECTS

Because of the long period of interest of uranium tailings confinement the likelihood of extreme events occurring is proportionately large. Floods occur from snowmelt, intense rainfall, or combined snowmelt and rain. The greatest rainfalls results form thunderstorms and tropical cyclones, which together with tornadoes, can also lead to potentially damaging high winds.

Records are short in Canada, generally a few tens of years, and thus extrapolation of data to predict 1000 year events is questionable. Even so the methodology is defined and in time estimates can be refined. Extreme years, such as 1980 in Canada, modify the picture, (Env. Can. 1981).

The period of record applies to a particular climate, which as we now know is not fixed in different parts of the earth. The uncertainties of the Canadian climate are being studied (Hare and Thomas 1974). There could be a global warming up (the greenhouse effect) with consequent melting of polar ice caps and flooding of low lying and coastal regions. Alternatively a minor ice age may develop with onset of glaciation and extensive permafrost. A shift of a few degrees either way apparently is all that is needed. Scientists are uncertain regarding their predictions, although theories suggest that major climatic change, principally a warming of about 2°C, will have occurred by the end of the next century, see Figure 8.1-1. Some point out that it may be beyond terrestrial effects anyway, linked rather to changes in solar activity. One thing seems fairly sure, however, from a study of past climate, and that is that it does change, and at time intervals of the order of a few hundred years (Lamb 1982).

8.1.2 GEOTECTONIC EFFECTS

Earthquakes, and in western regions, the possible effects of volcanism are potentially damaging. The earthquake activity in Canada is becoming better known, and probability estimates of seismic motion for the entire country have been published (Basham et al 1985). They are continually updated, as more data is accumulated particularly in the remote regions of the Northwest Territories, which are now thought to be rather more active than believed at one time. The worst effects of earthquakes are likely to be sudden failure of control structures due to liquefaction or slumping, and then consequent release of tailings. The remote possibility of siting an impoundment over a reactivated fault could obviously lead to a similar rupture in the embankment.

Good engineering design and construction control renders the risk of impoundment failure very low. Existing embankments constructed of uncompacted tailings sand need to be checked and possibly stabilized.

8.2 LONGEVITY OF EARTHEN STRUCTURES

8.2.1 PERMANENCE OF EARTHEN MOUNDS

Evidence of the permanence, or survivability that can be achieved in man-made earthen and masonry structures is found at a number of tombs. These earthen mound structures are conveniently found in such diverse climatic regimes as Siberia on the one hand and north Africa on the other. The time frame during which the structure have been preserved is in the order of thousands of years comparable to the lifespan required for uranium tailings impoundments.

The most obvious example is the 5000 year old pyramids of Egypt. These rock faced structures have remained intact with side slopes of 43°. The initial bolder attempts at pushing the side slopes to 52°, seemingly for aesthetic reasons, appear to have led to slope failures, (Mendelssohn 1971). Similar pyramids about 2000 years old are found in Mexico.

Less well-known are the frozen Scythian tombs high in the Altai Mountains of Central Asia. They are above-grade earthen mounds in permafrost ground, and they are believed to be around 2000 years old. The burial chambers are pits about 8 m square dug 5 m deep. The roofs were covered with timber and then a layer of coarse boulders was placed on top, followed by a mound of soil. The boulder layer had access to the air at the outside face. As a result in the winter cold air penetrated the chamber and being heavier than warm air it remained in the summer, the structure acting as a refrigerator. Permafrost was quickly established and many perishable items have been perfectly preserved in the burial chambers, (Artamonov 1965 and Rudenko 1970). This has some bearing on the preservation of above-grade tailings impoundments in Northern Saskatchewan.

In connection with the U.S. uranium tailings disposal has examined archaeological evidence for the survivability of earthen mounds in Europe, Africa, the New East and the U.S.A. has been studied in detail (Lindsey et al 1983).

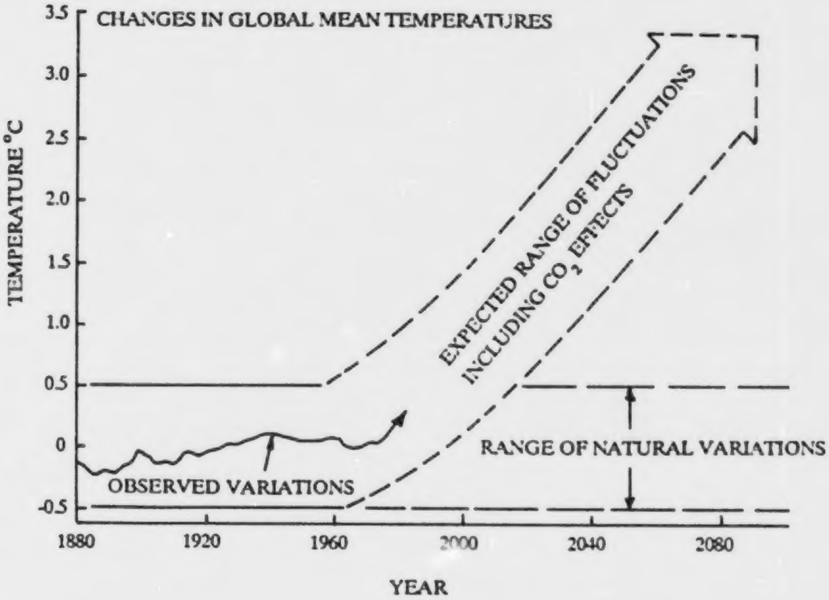


Figure 8.1-1 Actual and Projected Trends in Global Temperature 1880-2100 (Bruce and Hengeveld 1985)

8.2.2 FAILURE OF IMPOUNDMENTS

Less encouraging but nevertheless instructive in the design of earth impoundments is the knowledge of past failures. For our purposes impoundments can be thought of in two classes:

- storage of tailings, and
- impoundment of water for supply purposes or for power generation.

8.2.2.1 Tailings Dam Collapses

Most failures have involved the rupture of embankments constructed by the hydraulic-fill placement technique using the upstream method.

A number of failures have occurred as a result of liquefaction of the tailings during an earthquake leading to full hydrostatic earth pressure on the sloping outer face of the dam - examples of earthquake induced failures are the Chilean dams in 1965 and the Mochikoshi dam in Japan in 1978, (Jeyapalan et al 1983). Recently in 1985 in Chile a further two tailings dams failed during an earthquake. One was reportedly built by the downstream method and the other by the centreline method of embankment construction. Earthquakes apart, one of the worst disasters was the very recent collapse of the Stava tailings dams in the Dolomites in Northern Italy in 1985, when the villages of Stava and Tesero were swept away with a death toll of 269. Two overlapping dams failed during a period of exceptionally heavy rainfall. Although investigations are still on-going it appears that the dams failed not by overtopping but either by spontaneous liquefaction or a foundation slip in the upper embankment. Poor design and construction, and lack of regulatory inspection are being cited.

Other disasters are the well-known Aberfan waste dump in Wales, 1966, (Bishop 1973), followed by the Buffalo Creek impoundment in West Virginia in 1972.

8.2.2.2 Earth Dams Impounding Water

Water in flood is a particularly aggressive agent of destruction. Even so there are examples of ancient man-made, water retaining dams that have been built as far back as 2800 B.C., (Smith 1972). Many of the masonry and earthen dams built within the last two millenium within the confines of the ancient Roman and Persian Empires are still intact, even though many are not in use having silted up centuries ago.

Numerous natural landslides dams have formed in mountainous terrain all over the world. The dams have either failed within a very few months or years following their formation or they have remained as permanent features holding back lakes of all sizes. The permanence or otherwise of the natural dams is related to the size of the river and thus the quantity, and erodibility of the water flow, and to the size of earth debris forming the dam, and thus its resistance to being washed away. Even so there are very few natural dams that have persisted across major rivers, (Schuster 1986). Principally this is due to the inability of the dam, during subsequent overtopping, to develop a sufficiently erosion resistant spillway.

Relating this knowledge to the design of long-lasting tailing dams two lessons can be learned. First, in-valley impoundments are less preferable and should be placed in the smallest drainage basins possible, to minimize the size of erosive flow forces. Second, permanent, non-erodible spillway channels must be provided.

8.3 EROSION CONTROLS

The principal agents in the erosion of uranium tailings impoundments are water and wind. Water can erode by surface runoff, and by subsurface seepage and piping. Erosion of foundation and embankment soil, or tailings by means of subsurface seepage of water is an important aspect of stability. However, it falls more naturally into the discussion of barriers to seepage discussed in Section 7.3. Once stabilized by a surface cover, the action of wind tends to be less critical than that of water. Minor agents of intrusion leading to erosion are burrowing animals and possibly root action, and excavations and material usage by man. Erosion processes are summarized in Figure 8.3-1.

The general field of erosion studies is broad and multi-multidisciplinary and a number of important monographs have been written, (Bennett 1955), and a more recent compendium of European and Asiatic experience (Zachar 1982). With particular application to uranium tailings piles very useful studies have been carried out for the NRC (Nelson et al 1986 and Walters et al 1986) both documents referring back to earlier research work and reports.

In many instances site selection will be the most important factor in erosion control, but in reclamating existing sites the luxury of choice may not be available. It is imperative to consider the site selection process for any new projects and reference should be made to section 6.1.

Generally speaking uranium tailings sites in Canada are in the northern regions where the intensity of surface water erosion that occurs naturally is an order of magnitude less than that in the arid southwestern part of the USA. Transfer of technology from the USA to Canada therefore should proceed with this perspective in mind. The natural conditions in Canada have far more in common with much of the northern part of the Soviet Union. Although we do not have access to Soviet technology, useful data on soil erosion in the USSR is available (Zachar 1982).

8.3.1 WATER EROSION

One of the more likely mechanisms of long-term disruption of uranium tailings impoundments is surface water erosion.

For example at some sites the existing diversion and spillway structures have been designed for 1 in 100 or 1 in 200 year flood events. In consequence the as-designed flow is likely to be exceeded several times during the period for which tailings impoundments are required to be effective, i.e., 1000 years. Probability theory leads us to believe that during the required effective life of the impoundments, the probability of the 1000 or 5000 year floods arising is 63% and 18%, respectively. Thus, some degree of flood erosion of diversions and spillways, will surely occur unless larger flow conditions are designed for in abandonment measures (McInnis 1985 and SRK 1986).

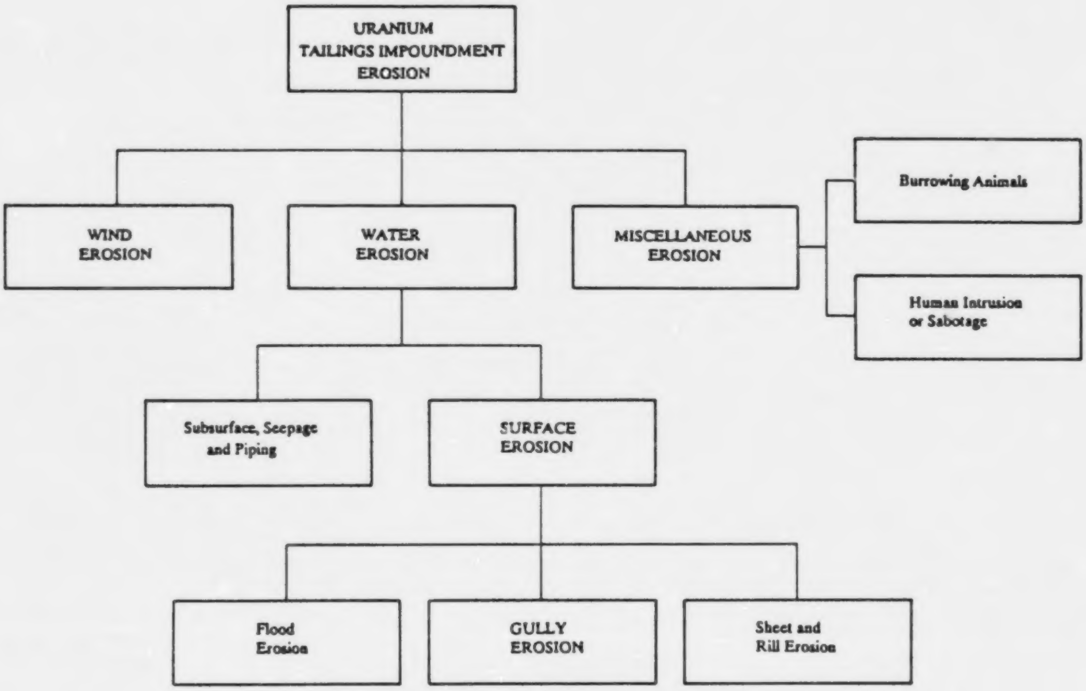
8.3.1.1 Erosional processes

Although somewhat interrelated three separate surface water erosional processes can affect a tailings impoundment:

- floods can erode in pre-existing channels such as diversion channels, spillways or in streams and rivers adjacent to the structures,

- rapid, concentrated scour can develop during intense rain leading to gully erosion on slopes in low areas and depressions, or where excessive rill development has been allowed to proceed, and

- raindrop erosion, and sheet and rill erosion can occur over relatively flat areas.


URANIUM TAILINGS IMPOUNDMENT EROSION
WIND EROSION
WATER EROSION
MISCELLANEOUS EROSION
Burrowing Animals
Human Intrusion or Sabotage
Subsurface, Seepage and Piping
SURFACE EROSION
Flood Erosion
GULLY EROSION
Sheet and Rill Erosion

Note: Principal agents of erosion in upper case letters.

Figure 8.3-1 Erosion Processes

The last two processes are often referred to as overland erosion. It is caused by the movement of water over and through the surficial soils. The process grades into the region of subsurface flow, where seepage can lead to piping erosion or deep-seated embankment instability, as already discussed in Section 8.3.

Erosion is influenced by the permeability of the surface layers since excess water that cannot infiltrate through the soil must overflow on the surface.

a) Flood erosion

Flood protection must consider the rate of water flow down a particular channel. This involves estimation of the design floods resulting from prescribed design storm events.

Commonly used events are the 1 in 10 year event, the 1 in 100 year event and the Probable Maximum Flood (PMF). On the average a 1 in 10 year event might occur once every 10 years. However, in the short term there might be several 1 in 10 year events in a 10 year period.

It should be noted that the term "design storm event" is applied to both storm rainfall and storm runoff. The 1 in 10 year rainfall event will not always produce the 1 in 10 year flood event. Storm runoff is very dependent on antecedent moisture conditions. A severe event following very dry conditions may produce only a small runoff, while a small event following a wet period could produce a large flood. It is also necessary to assign a rainfall duration to the return period of a rainfall event. For example, the 1 in 100 year, 1-hour rainfall depth might be 50 mm and the 1 in 100 year, 24-hour rainfall depth 120 mm.

The PMF as defined by the United States Corps of Engineers is the flood that may be expected from the most severe combination of critical meteorological and hydrological conditions that are reasonably possible in the region. The rainfall associated with the PMF is known as the Probable Maximum Precipitation (PMP) and is defined as the theoretically greatest depth of precipitation for a given duration possible over a particular drainage basin at a particular time of year. The PMF design event is the most stringent hydrologic design criteria that can be applied. It is only used if the consequences of failure might be catastrophic or if the design life of the structure is long (at least 100 years). Nevertheless, it is commonly used in Canada on mining prjoects. It has been standard practice at Elliot Lake uranium mines for the past 10 years. Many are designed to store a regional storm (~ 1000 year return) and pass excess flows over the spillway, which are designed assuming that all diversion ditches fail, directing water into the tailings pond. The design event suggested for evaluating the long-term stability of a reclaimed tailings impoundment in the USA should be the PMF, (Nelson 1986). The same recommendation has been restated in the NUTP studies (SRK 1986).

This may seem conservative, but probability theory can be used to demonstrate the logic behind these recommendations. Consider a project with a 100-year design life. It is often imagined that if the 1 in 100 year storm event is used as the basis of design the probability that it will occur during the design life is 100%. Probability theory shows that there is a 63% chance that the design capacity will be exceeded at least once during the design life. Similarly for a 200 year design life using the 1 in 200 year flood data the probability of exceedance at least once is again 63%. Using the 1000 year event for a 200 year design life the probability of exceedance becomes 18%. For the 10,000 year event the corresponding probability is 2%. This might be regarded as acceptable. But in reality because of our limited data base we know very little about the true magnitude of the 1000 year event, let alone the 10,000 year event. Thus the use of the PMF concept is considered to be a reasonably pragmatic choice. Conditions under which events less than the PMF may be acceptable (Caldwell et al 1986).

Flood flows associated with a particular return period are either determined from streamflow records or calculated on the basis of rainfall information and knowledge of the flood characteristics of the catchment. In determining design flows for tailings impoundments, estimates will usually be made based on rainfall and catchment information. Regional relationships between streamflow rates and catchment characteristics can provide a very useful means of determining design flood flows.

Although not strictly correct, it is generally assumed that flood flows for a given return period will be produced by storm events with the same return period. Thus the rainfall depth associated with a 1 in 100 year rainfall event is used to determine the 1 in 100 year peak flood flow. The PMF is determined based on the PMP and if high runoff conditions are assumed (i.e., wet antecedent moisture conditions or frozen ground) errors in relating the PMF to the PMP will generally be small. However, it should be noted that in regions where peak flows are caused by snowmelts it is not appropriate to make flood estimates based on storm rainfall information.

Streamflow records and surface water data for Canada are published on an annual basis by the Water Resources Branch of the Department of the Environment in Ottawa. Additional information is presented in the Hydrological Atlas of Canada, Minister of Supply and Services (1978). Procedures for determining flood flows when such data is available are standard (Barfield et al 1981).

In many of the remote regions in Canada where mineral deposits are located no records exist of streamflow and surface water data. Under these circumstances flood flow determinations can be made empirically based on rainfall and catchment data. Design rainfall depths for different return periods are presented in the Hydrological Atlas of Canada. These maps have been developed from depth duration frequency curves for different weather stations throughout the country. In general, historical rainfall records are only available for periods of less than 100 years and it is necessary to extrapolate to make PMP estimates. Point information and maximum storm information from adjacent catchments is often transposed to obtain areal PMP estimates.

A number of flood flow estimation techniques have been developed. The most commonly used are:

- empirical equations,
- unit hydrograph approach,
- time-area method, and
- kinematic approach

The use of these four techniques is described in detail (SRK 1986).

The impact of flood intrusion will depend on the proximity of the river to the impoundment, flow velocities and the protection characteristics of the toe of the impoundment. If flood flows are in contact with the toe, some degradation can be expected. This is considered unacceptable unless protective measures (such as the placement of a riprap) have been installed at the toe.

It should be noted that adequate protective measures are difficult to design unless the behaviour of the river can be predicted. Therefore it must first be established if vertical or horizontal instability in the river is a factor. The theoretical aspects of fluvial instability are described elsewhere (SRK 1986). The possible impact of changes in the river on the impoundment must be assessed. If they could be a factor, control measures need to be constructed along the river course or protective measures taken at the toe of the impoundment.

Existing Canadian uranium tailings impoundments are not in locations threatened by river flood erosion. With the emphasis on minimizing the upstream drainage area above impoundments, most sites developed during the last decade have been located in the upland drainage basins of river systems. Here the major concern is the potential for gully encroachment and erosion on the impoundment.

A few inactive impoundment sites are located in the lower reaches of stream systems where flood intrusion and the possibility of river channel changes could be a concern. If future sites are considered alongside the downstream stretches of a river or stream the possible impacts should be investigated (Schumm and Chorley 1983). The impacts could be either erosional or depositional leading to overbank flooding or meandering.

The transporting power of a stream in terms of the mass of material moved increases enormously with increase in its velocity, variously estimated at between the 6th and 7th power. In addition abnormally high water levels can be reached for brief intervals of time. This is attributed to bore or slug flow, whereby super critical flow overtakes and overrides the subcritical flow. The phenomenon has the appearance of a series of standing waves separated by troughs marching in unison down the stream, (Caltrans 1970). The danger these slug flows pose is in their ability to scour material far higher up the banks of a channel than might be expected. Although not too common on natural streams similar slug flow has been observed on steep mountain creeks during torrential flow when sizeable quantities of debris are being transported, (Russell 1972). It is fairly common in trained channels and lined ditches.

Particular attention must be paid to the impact of floods on diversion ditches, impoundment spillways and water treatment storage areas.

Erosion, as a consequence of diversion failures following blockage by vegetation, debris, sediment or ice, is considered to be a major potential cause of uranium tailings releases. Vegetation growth is expected along all stream channels, particularly where these are intermittent. Such vegetation becomes an impediment to flow resulting in both sedimentation and debris accumulation. Blockage can be rapid. Glaciation, the build up of ice in ditches during a single winter, has been observed to cause blockage in a single season. Erosion of the displaced flow during the spring thaw can result in channel relocation. Unless the damage is repaired immediately, this can result in fairly rapid realignment or meandering of the stream channel. Regular maintenance is considered to be the only appropriate control measure.

Diversion and spillway failure could be anticipated at each of the generic Canadian tailings sites as currently designed (SRK 1986). The amount of channel erosion that would occur with such failure was estimated for the Saskatchewan Wet Tailings site at up to 0.2 m for the 2 year event and over 1 m for the 100 year event. These rates of release of tailings would be unacceptably large.

As a rough guide to scour potential, safe permissible velocities measured in established canals in the USA range between 0.5 m/sec in fine sandy soils up to 2 m/sec in coarse gravel and cobbles, (SRK 1986).

Under typical Canadian conditions an important consideration is the impact of blockages due to debris or ice. With the development of a forest type cover a considerable amount of forest debris will be produced. Some of the thickest vegetation cover may develop adjacent to the diversion structures. Sedimentation is expected in the flatter portions of diversions as well as behind any blockages that occur. It is anticipated that, in the absence of maintenance of the diversion structures, blockages due to sedimentation and debris will be a regular occurrence. Ice formation and iceflows may also produce blockages in drainage ways, particularly during spring.

Once a blockage occurs the following consequential failure can result:

- flooding of a portion of the impoundment cover resulting in a killing off of vegetation cover and increased infiltration, and

- flow outside of the designed, erosion protected flow channel. This may result in rapid scour of the adjacent terrain and failure of the diversion structure. This will in turn result in additional scour and general erosion.

b) Gully Erosion

Following closely on the above discussion is the process of gully erosion by the loosening and transporting of soil particles during concentrated water flow. It has been identified as a major long-term stability concern of uranium tailings impoundments.

An intensive field investigation was made for the Nuclear Regulatory Commission (NRC) , and a method of assessment proposed, (Falk et al 1985 and Nelson et al 1986). It is perhaps the only method applicable to analyses for embankments and covers. It has some restrictions as follows:

- developed from data limited to the arid Western United States,
- not developed specifically for uranium tailings data,
- does not account for variations in vegetation cover,
- based on data for impoundments no more them 35 years old. Not recommended for time periods longer than 200 years, and
- in colder regions, soil erosion depends on the thawing of surface ice or upper layer of permafrost. Frost action also loosens the surface layers making them more susceptible to erosion.

Using this method, estimates have been made of gully erosion depths for a 200 year period at the generic Canadian tailings sites. Deep gullying can be expected up to about 5 m in erosion susceptible materials such as tailings, or silty and sandy tills. Steep side slopes on embankments at 2H:1V constructed of semi-dry tailings can be expected to fail completely as a result of excessively deep gully erosion. Covers will suffer a similar fate. The use of waste rocks at the generic model site significantly reduce the depth of gully but it does not eliminate the problem, because the size of the rock used is too small (mean rock size 5-20 mm) and the grading is uniform.

In making estimates of depth of embankment gully erosion it was assumed that no water would drain from the cover over the embankment crest. If the effective drainage area was increased by drainage from the cover then the depth of gully erosion would increase greatly. This highlights the need to ensure that long-term drainage on the surface of the impoundment should be away from the embankments and towards a secure erosion resistant spillway.

Since perimeter diversion ditches are insecure because of the potential for their blockage, careful consideration must be given to the final shape of the impoundment surface to enable drainage to be achieved without the use of ditches located in close proximity to embankment crests.

The estimated gully depths that are expected to develop on covers with inadequate erosion protection are large and may be expected to be even larger if a 1000 to 2000 year time frame is considered. Field experience of gullying is that deep gully formation can be anticipated in less than 200 years in both tailings and till type materials. The accuracy, but not the prediction of deep gullying, of the Falk method is questionable, and furthermore, it does not adequately reflect the erosion resistance offered by a heavy vegetation cover, particularly forest cover, or of coarse waste rock or riprap cover materials.

From the results of this evaluation, however, it was concluded that:

- deep gulley erosion could be anticipated in all the tailings and till covers,
- a thin (600 mm) waste rock cover might resist gully erosion for a period but once breached it would be of limited effect,
- current gully estimating technology is inadequate to determine the gully resistance from forest cover or coarse waste rock. It is anticipated that these cover types would demonstrate significantly lower gully potential than is predicted by the method of Falk,
- contour drainage, using riprap lined ditches to reduce gully tributary areas, would be an effective method for gully erosion control. All ditches will require long-term maintenance, and
- careful consideration must be given final shaping of the tailings cover to minimize the use of ditches and, as far as possible, to locate these away from the immediate vicinity of embankments.

Table 8.3-1 (Kosov et al 1976) for central regions of the USSR presents calculated critical velocities at which gullying starts. This data is a useful comparison for Canadian purposes.

TABLE 8.3-1
CRITICAL WATER VELOCITIES FOR VARIOUS SOIL AND ROCK TYPES

Characteristics of soil and rock	Water velocity [m s^{-1}]
A. Loose quaternary sediments	0.3-2.0
1. Sand of all grain sizes	0.3-0.55
2. Loess and loess earth, peat	0.65-0.75
3. Loam of marine origin	0.55-1.0
4. Heavy clay	1.0-1.3
5. Compact earth	1.0-1.5
6. Gravel loam of different origins	1.5-2.0
B. Sediments and frozen rocks	2.1-6.0
7. Soft sediments (cretaceous, solonetzic)	2.1-3.1
8. Limestones	2.5-4.5
9. Hard sediments (sandstones)	5.0-6.0
10. Frozen quaternary rocks	5.0-6.0
C. Very hard crystalline rocks	6.0-25.0
11. Tuffs and similar rocks	6.0-16.0
12. Monolithic crystalline rocks	16.0-25.0

Considering conditions in Northern Canada the following opinion (Zachar 1982) pertaining to the Soviet Union considers gully erosion from a different perspective;

> "The most important factor governing gully erosion is the climate, since this determines the aggressivity of the erosion process and the rate and type of plant growth - the most important element in erosion

> control. In general, the intensity of gully erosion increases from the tundra and forest-tundra regions, where potential gully erosion is very low, to the taiga zone with low to moderate erosion and to the forest zone with moderate potential erosion. In the steppe and forest-steppe zones the rain erosivity is approximately the same, compared with the former regions, but owing to the higher temperatures the protective effect of vegetation is usually less, and therefore potential erosion in these zones is, as a rule, greater."

c) Sheet and Rill Erosion

Uranium mill tailings clearly have a high potential for sheet erosion, which is defined as that occurring as a result of impact of raindrops loosening surface soil which is then transported by wind and by water flowing in small ephemeral rills. On sloping ground minor undulations rapidly lead to the development of rill channels.

The intensity of rill erosion depends largely on the energy and transporting capacity of flowing surface water rather than on impact by raindrafts, (Zachar 1982). The rapid growth of rill erosion in low resistance materials leads to gully formation by the concentrated channeling of water flow.

The commonly used American methods of predicting soil losses are:

- universal Soil Loss Equation (USLE) for gross losses over an area, and
- modified Universal Soil Loss Equation (MUSLE), used to determine sediment yields from single storm events.

The empirical coefficients used in these equations are based on data in the USA and modifications are necessary for conditions in Canada. Computer codes can be used for MUSLE calculations (SRK 1986).

Using this approach erosion release rates for a 1000 year time frame have been calculated for the generic Canadian tailings impoundments and led to the following conclusions:

- sheet and rill erosion of the embankments is not expected to be significant or cause instability of vegetated or riprap covered slopes. Only in the case of the semi-dry tailing site, with its highly erodible embankment material, is significant sheet erosion expected, and
- sheet and rill erosion will lead to instability and unacceptable release rates for covers consisting of bare or sparsely vegetated tailings, and thin (600 mm) non-vegetated, silty till. Vegetated till or waste rock covers would be stable in the long-term with respect to sheet and rill erosion.

Observations on archaeological mounds, (Lindsey et al 1983), and photographs of rill and gully development on existing tailings impoundments in Colorado and New Mexico, (Walters and Skaggs 1986), suggest that overland erosion is more common in arid climates. In the wetter climates vegetation once established tends to prevent serious overland erosion provided that steep side slopes (1H:2V) and saturated soil do not lead to slumping.

8.3.1.2 Protection and Stabilization

Site selection to ensure that tailings impoundments are sited outside major flood plains is the most effective design measure against flood intrusion. If this is not possible heavy riprap or special erosion control measures will be needed. The potential for diversion and spillway structural failure can be high. Appropriate design measures to guard against this eventuality would be:

- design for the PMF with ample width and size to allow for sedimentation and partial blockage by vegetation, sediment, debris or ice. Under no circumstance should culverts be used, since they block easily, and their long-term structural integrity is in doubt, and

- use of heavy riprap, either waste rock or specially quarried rock, along the base and side slopes of flow channels.

To guard against sheet erosion under Canadian conditions it is believed that establishing forest cover, or a thin layer of rock waste, or riprap will ensure adequate long-term stabilization of surfaces with slopes less than 5%. On slopes steeper than 15% riprap is considered necessary. Between 5 and 15% appropriate measures will depend on embankment material type, slope length and vegetation type. In general the mitigative measures required to protect against gully erosion will prevent sheet erosion.

Gully erosion can be controlled in three ways:

- installation of an erosion resistant layer: Current technology does not permit a realistic estimate of the effect of forest cover, and additional research is warranted. Heavy riprap cover is the only tried and proven technique considered appropriate for long-term embankment stabilization at the slopes commonly associated with tailings embankments in Canada.

- reduction of drainage areas contributing to gully erosion: The construction of berms and diversion ditches to limit catchment areas is cost effective. Since embankment slopes have relatively small surface areas the prime control is prevention of surface drainage over the crest of the embankment, and

- flattening of slopes: Flattening of the slope increases the drainage area. The benefits to be gained with respect to the total depth of erosion are small. Flattening the slope does provide additional cover on the downstream slopes, which would allow considerably more erosion before the embankment becomes unstable.

The design criteria used for UMTRAP requires the maximum design slopes for both tailings and cover do not exceed 20 percent, i.e., 5H:1V. This criterion is not necessary for erosion control in Canada, although it has merit with regard to the control of solifluction resulting from frost action.

For cover protection, waste rock or quarried riprap may be cost effective, and it is reliable in preventing gully formation. However, in itself it does little to prevent frost heave or radon emanation, and it clearly increases infiltration. Alternatively thin soils, provided that they are secured by a stable forest blanket, are considered to be a cost effective cover type. Thick soil covers are likely to be effective at most locations, although they may be costly to construct. Rock should be used in semiarid regions where the surface of the cover slopes at more than 3 to 5°.

In recent years it has been realized that tailings covered by at least 2-3 m of water may be a viable solutions. Such an approach can be taken with disposal in natural lakes or artificially below grade excavations. Lake disposal, as practiced at the Beaverlodge Mine has been shown to be cost effective and secure in the long-term. Underwater disposal had been considered for Quirke Lake in the Elliot Lake region, but rejected because of concerns about short term water quality and increase stress incurred in the underground mine.

Riprap can be designed according to a number of reliable engineering methods. In steep channel slopes greater than about 10% the size of the riprap may be far greater than the depth of water flow and methods of design are less reliable. Alternatively in steep diversion channels and spillways, drop structures or check dams can be used. Check dams, however, to be secure in the long-term must not be constructed of unbonded rock or masonry. Considerable experience exists with the long-term performance of mountain stream regulation works in Europe, and where appropriate such regulation works should be constructed. The design of riprap specifically with respect to uranium impoundments has been discussed in considerable detail (Walters et al 1986, Nelson et al 1986), who describe four methods as follows:

- safety factor, (see also Richardson et al 1975),
- Stephenson,
- U.S. Corps of Engineers, and
- U.S. Bureau of Reclamation.

In designing riprap careful attention is paid to the selection of the rock type, the gradation of the material and the provision of underlying filter layers. Rock durability is of obvious importance. Filters prevent migration of bedding or barrier layers through the riprap (Sherard et al 1984).

According to extensive studies by the California Division of Highways on the protection of river banks and shorelines (CALTRANS 1970), riprap has a number of advantages. These apply as well to uranium tailings impoundments:

- riprap is flexible and is not impaired or weakened by minor embankment settlement,
- local damage or loss is easily repaired. Additional rock can be added at the toe to offset possible scour,
- construction is not complicated and no special equipment is necessary,
- appearance is natural,
- if riprap is exposed to fresh water, vegetation will often grow through the rocks strengthening the embankment material and restoring natural roughness,
- wave run-up is less by as much as 70% with riprap than with smoother surfaces,
- riprap can be salvaged and may be stockpiled and reused, and
- riprap is less susceptible to ice damage than are other protection methods.

The last point is important under Canadian conditions.

Valuable field experiences on the durability of riprap and rockfill together with design and construction details has been documented in connection with rockfill dams used for flood control, water supply and power generation, (ASCE 1960). Some of these dams are now more than 100 years old and performing satisfactorily. Many are located in the western States particular in California, where they evolved from practices used in the gold mining regions of the Sierre Nevada in the 1850's. In assessing long-term performance this experience is useful. Noteworthy is the tremendous inherent stability of rockfill. In the early structures side slopes of 1.5H:1V were thought to be conservatively flat, and stable slopes of 1H:1V and steeper were not unusual.

In the Canadian environment the use of forest cover for protection would seem to be a viable method; much more so than in the USA, where many of the sites are located in arid regions. As a result little guidance is found in NRC publications with the exception of the work on grass and shrub revegetation (Beedlow 1984 and Voorhees et al 1983). Long-term experience with forest cover in artificial circumstances in North America is limited, although forest management practices in replanting can be called on. Reforestation practices in Europe go back further and resulting control of erosion is well documented, (Zachar 1982 and Mougin 1931). Simple revegetation techniques are applied in civil engineering practice (Gray & Leiser 1982). The obvious effect of revegetation and forest cover in minimizing soil erosion in wetter climates can be judged from Figure 8.3-2. In general the climax vegetation in Canada is forest in contrast to grassland at most uranium tailings sites in the United States. A limitation of forest cover results from the occurrence of forest fires and the consequent potential for soil erosion, at least on the short-term, since forest fires are usually followed by rapid regrowth (SRK 1986).

8.3.2 WIND EROSION

Soil erosion by wind is a part of aeolization which includes all geomorphological processes such as erosion, deflation and accumulation that result from wind action.

Wind erosion can be as important as water erosion, particularly in hot regions lacking precipitation, i.e., in arid regions. The decisive factor is vegetation which is directly related to aridity.

Apart from the Interior of B.C., wind erosion is less of a factor in Canada, than in the South Western United States or Australia, at least on inactive tailings piles. Wind erosion of Canadian tailings is in general secondary to water action. Nevertheless, wind erosion of the loose granular tailings can still be substantial as observed at the Gunnar site, (SRK 1986) and can be accelerated by frost action.

Erosion of fine soil by a strong wind occurs if the ground is bare with a loose, dry surface. Such conditions can arise during beach deposition of tailings and during the early years of reclamation. As vegetation gets established wind erosion should cease, unless the vegetation is disturbed, re-exposing the soil.

Wind erosion leads to of what is sometimes termed "fugitive dust". Airborne particles can cause atmospheric pollution and safety hazards due to loss of visibility. The worst problems, however, are likely to be:

- transport of uranium and radioactive daughter products considerable distances from the site, up to 8 km (Schwendiman 1980) in the US; also the concentration of radionuclides in the smaller size of tailings particles, and
- deterioration of the cover.

With proper design of cover and control structures wind erosion is not a long-term concern, since measures designed to protect impoundments from water erosion are more than sufficient to protect against wind. Furthermore evidence from archaeological mounds, (Lindsey et al 1983) suggests that wind erosion of uranium impoundments is unlikely to be a problem if proper abandonment measures are undertaken.

8.3.2.1 Erosional processes

Books have been written even on this one aspect of erosion, (Bagnold 1954). According to him, transport of soil grains by wind shear stresses occurs three ways:

- by rolling or sliding of large particles (> 1 mm) along the surface,
- by saltation, particles bounding through the air, returning to the ground and dislodging other, and grains
- in suspension, small particles (< 0.1 mm) moving with the turbulent airstream.

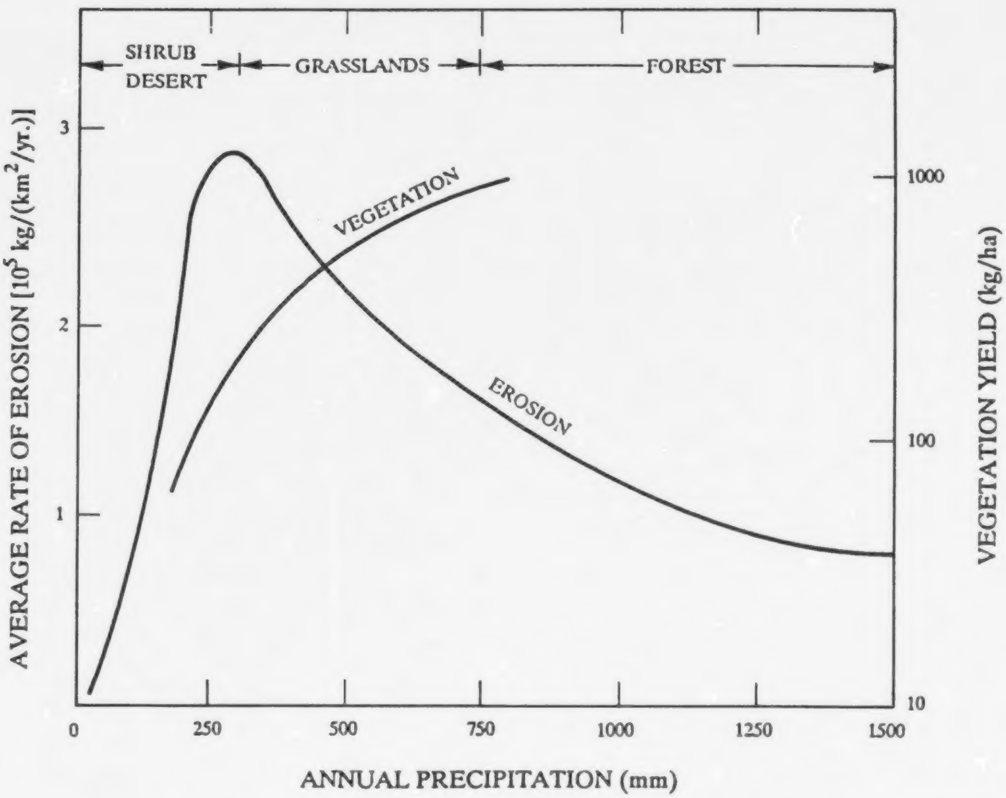


Figure 8.3-2 Influence of Precipitation on Production of Vegetation, and on Erosion (adapted from Langbein and Schumm 1958)

The greatest mass movement occurs by saltation. Soil loss is directly proportional to the cube of the wind speed, however, particles larger than 3 mm are only transported by hurricanes and tornadoes. Experimental studies of wind erosion of uranium tailings particles has been reported for NUTP in (AER 1986).

The movement and circulation of air is the main factor in the process of wind erosion. Wind drys the surface layers and the fine grained, non-cohesive particles blow away. The stronger the wind the greater its influence on the soil. The soil does, however, offer some drag resistance to the wind, reducing its velocity.

As a result the potential wind erosion loss of a soil E can be expressed by the basic equation,

$$E = VP$$

where V is the wind erosivity and P the soil erodibility.

Research in the agricultural lands of the Great Plains in the 1950's led to the commonly used equation (Chepil and Woodruff 1963),

$$E = f\,(IKCLV)$$

where I is the soil erodibility factor,
K is a soil surface roughness factor,
C is a local climate factor,
L is the field length in the direction of the wind, and
V is a vegetative cover factor.

Use of this method for the determination of the annual loss for a given area has been discussed in detail (SRK 1986b) where choice of the appropriate parameters is explained together with examples for embankment and covers of generic Canadian uranium tailings sites.

The method, developed for agricultural use, seems applicable to soils having a fairly uniform grain size, and it is useful for estimating losses at tailings sites. On bare tailings it predicts high losses consistent with observations at the Gunnar site, where wind transported tailings up to 1 m depth have been reported. Even with grass cover it is predicted that tailings will be eroded away to depths of the order of 10 m in 1000 years. However, depending upon particle gradation, till covers 3 m thick with good grass cover may be wind resistant for 1000 years or more. Forest cover is expected to reduce wind erosion to a small fraction of this.

Where well-graded till forms the cover material theoretical estimates of erosion losses using the above formula are likely to be excessive leading to unduly conservative designs. This is because the theory takes no account of the greater erosion resistant properties of well-graded materials. The fine particles blow away leaving the coarse stones behind. This leads to the formation of a protective layer known as stone pavement, or desert armour. Such a process would lead to stability of a cover. Hence a till with a large gravel content, 30 to 40%, would form an effective wind resistant cover. It is estimated that deflation of the order of 0.1 m would be all that need occur before an armoured surface forms in such materials.

8.3.2.2 Permanent Protection and Short-Term Stabilization

The crusting that can occur on the surface of dried tailings tends to be unstable as a result of repeated wetting, drying, freezing and thawing. Under these conditions it is susceptible to wind erosion and cannot be relied upon. On abandonment tailings require permanent wind protection. Riprap covers, or combined rock or self-armouring soil and vegetative covers, particularly forest covers, are very effective in eliminating wind erosion. Similar treatment on the side slopes of impoundment structures works equally well. Permanent water covers are also effective but the peripheral beach zones should be treated with riprap.

Other means of protection include windbreaks, either natural or artificial. Shrubs and trees act as partial barriers reducing wind speeds. Another benefit from windbreaks is reduced evaporation and increased soil moisture content generally leading to a promotion in growth of vegetation. Because synthetic windscreens tear, they tend to be short-term solutions for 5 to 10 years, or less.

Short-term benefits during the operational phase of tailings deposition can be achieved by soil stabilization and dust suppression techniques, such as spraying with water or chemicals. The simplest method is water sprinkling, but there is some evidence to suggest that repeated wetting and drying makes the surface more fragile and actually increases the potential for wind erosion. Numerous chemical stabilizers have been field tested for durability. The most effective chemical stabilizers appear to be synthetic polymers such as latex and acrylic emulsions. They last for up to one year although the material cost are high compared to asphalt emulsion or hydro mulch which, although less durable, may be just as cost-effective. A chemical stabilizer acts by binding the tailings particles together to form a continuous protective film or crust over the surface. Chemical stabilizers are readily available. Typically they are diluted with water and sprayed onto the tailings surface.

A combination of windscreens and chemical stabilizers may provide the optimal short-term solution to fugitive dust problems, (Elmore and Hartley 1985).

8.3.3 MISCELLANEOUS EROSION

Wind and water are potentially by far the most disruptive forces on uranium tailings impoundments.

A number of other possible mechanisms exist. They should be considered on a site specific basis. Miscellaneous mechanisms of erosion or intrusions that could possible take place are:

- intrusion by burrowing animals either through the cover leading to radon flux increase or through embankments leading to piping erosion. It is thought to be less of a problem in Canada. Biotic intrusion barriers, in the form of a coarse gravel layer can be included in the cover, should it be required,
- intrusion by man. Use of tailings, as a construction material and for fill has been a major cause of tailings distribution into the environment in the USA. Such usage has not occurred in Canada. Obliteration for agricultural or industrial land requirements seems to have been a significant mode of disturbance of ancient man-made earthen mounds, see the archaeological evidence (Lindsey et al 1983). Deliberate sabotage is a possible failure mechanism, although unlikely in remote regions. Inadvertent human intrusion can be guarded against by fencing and posting signs. To a large extent, however, the prevention of human intrusion depends on the maintenance of institutions, which involves sociological issues beyond the scope of this manual, and
- tree root action through covers will result in the long-term modification of the physical properties of the cover. Rapid clogging of shallow drainage layers could occur.

Miscellaneous intrusion by humans, animals, vegetation and biobarriers to prevent intrusion have been considered (Cline et al 1982 and Young et al 1986).

8.4 FROST ACTION

8.4.1 GENERAL

Frost action can influence the long-term stability of covers, structures and drains.

The main concern with respect to cover design is the potential for vertical displacement (heave or settlement) and the resulting effect upon surface drainage. Secondary concerns are frost effects upon cover permeability and the potential for freezing and thawing to transport pore fluids.

The effect upon structures is related to frost heaving. Repeated freezing and thawing can induce preferred seepage paths in high silt content embankments increasing the risk of piping failure. Frost can deteriorate concrete control structures by direct action on the concrete itself and by frost heaving of the foundation soil.

The following subsections discuss the applicable thermal processes in light of conditions at the Gunnar, Key Lake and Rabbit Lake tailings impoundments.

8.4.2 GROUND THERMAL REGIME

The thermal destiny of the tailings is the central thermal issue. Will frozen tailings ultimately thaw? If so, how fast? Might permafrost aggrade in unfrozen tailings thus immobilizing pore fluid? Of secondary concern is the amount of seasonal freezing or thawing under varying cover and surface conditions.

The thermal aspects are discussed in detail elsewhere (SRK 1987). When the ground surface is exposed to freezing temperatures, pore water in the soil freezes. The rate and extent of freezing/thawing is controlled by:

- heat conduction within the soil,

- heat exchange at the ground surface.

Heat conduction theory is quite well understood. Soil freezing is complicated somewhat by the latent heat of freezing of the soil moisture. The soil parameters required to characterize heat conduction are the frozen and unfrozen thermal conductivity and specific heat of the soils as well as the latent heat of freezing. Each of these parameters depends primarily upon the dry density and moisture content of the soil. Heat exchange at the ground surface is more complex. The heat balance depends upon meteorological conditions as well as vegetation and surface characteristics.

The technology for ground thermal predictions is quite well developed. Simple thermal models are available (Andersland and Anderson 1978) to estimate the depth of seasonal freezing and thawing. They are inadequate to estimate long-term thermal equilibrium. The thermal model developed by EBA Engineering Consultants (SRK 1987) is capable of predicting long-term thermal conditions. The data requirements consist of the moisture, density and mineralogical characteristics of the soils to estimate soil thermal properties. Meteorological and site surface condition information is necessary to estimate the ground surface heat exchange conditions. The model requires calibration to measured soil temperature profiles to provide confidence in long-term predictions. This requires installation of temperature measurement cables and monitoring temperature for 1 to 2 years. Once the model can be calibrated to predict existing conditions, changes under different surface or cover conditions can be predicted with confidence.

Thermal modelling was carried out at the Gunnar, Key Lake and Rabbit Lake sites using the EBA computer thermal model. Results are summarized in Table 8.4-1. The geothermal conditions in

TABLE 8.4-1
SUMMARY OF THERMAL ANALYSIS

ANALYSIS NUMBER	TAILINGS PROFILE	INITIAL GROUND TEMPERATURE	WIND SPEED	SNOW DEPTHS	EVAPOTRANSPIRATION	PREDICTED GEOTHERMAL CONDITIONS	SEASONAL FREEZE/THAW DEPTH (m)	YEARS OF TAILINGS TO FREEZE (THAW)
GUNNAR								
G1	Fine	0°C	Normals	Normals	0.0	Seasonal Freezing	2.2	-
G2	Fine	0°C	Normals	10 percent	0.0	Seasonal Freezing	5.2	-
G3	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	3.0	21
G4	Fine	-2°C	Normals	Normals	0.0	Permafrost Degradation/ Seasonal Freezing	2.4	(9)
G5	Coarse	0°C	Normals	Normals	0.0	Seasonal Freezing	2.7	-
G6	Coarse	0°C	Normals	10 percent	0.2	Seasonal Freezing	4.0	-
G7	Fine	0°C	1.5 x	Normals	0.0	Seasonal Freezing	2.5	-
G8	Fine	0°C	1.5 x	Normals	0.2	Seasonal Freezing	2.9	-
G9	Fine	0°C	1.5 x	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	2.0	4
G10	Fine	0°C	Normals	Normals	0.5	Seasonal Freezing	3.1	-
KEY LAKE								
K1	Fine	0°C	Normals	Normals	0.0	Seasonal Freezing	1.3	
K2	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	1.3	4
K3	Fine	0°C	Normals	50 percent	0.5	Aggrading Permafrost/ Seasonal Thawing	1.7	4
K4	Fine	-2°C	Normals	Normals	0.0	Permafrost Degradation/ Seasonal Freezing	1.3	(13)
RABBIT LAKE								
R1	Fine	0°C	Normals	Normals	0.0	Seasonal Freezing	21	-
R2	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost Seasonal Thawing	1.5	100
R3	Fine	0°C	Normals	50 percent	0.5	Aggrading Permafrost/ Seasonal Thawing	1.5	<100
R4	Fine	-2°C	Normals	Normals	0.0	Gradual Increase in Active Layer Thickness	3-4)	

Saskatchewan are very close to the balance point between aggrading and degrading permafrost conditions. For example, at the Gunnar site frost boils have been observed (BBT et al 1986) which are about 1 m in height with a permafrost core frozen to a depth of about 5 m. The boils are located adjacent to standing water where the water table is at surface. The formation of the boils could be modelled. Permafrost is initiated by high evapotranspiration and resulting heat extraction during the summer months. Heave resulting from freezing elevates the ground surface. In the following winter the depth of insulating snow is less on the elevated area and the permafrost condition is perpetuated. In other portions of the Gunnar site where the water table is at depth, evapotranspiration is low and thawed conditions are favoured. Thus very subtle changes in ground surface conditions can make the difference between aggrading and degrading permafrost conditions.

At Key Lake non-permafrost conditions are favoured. The seasonal depth of freezing and thawing is much less than at Gunnar because of the much higher moisture content tailings with greater latent heat content.

At Key Lake and Gunnar sites, frozen tailings which may have been incorporated into the tailings mass during winter deposition, would likely thaw with time. It is expected that a completely frozen section of tailings would take 10 to 20 years for compete thaw. At Rabbit Lake the thermal conditions are closer to the balance point between aggrading and degrading permafrost. The thermal analysis indicated that thawing is favoured; however, the complete thawing could take more than 100 years.

The covers (with exception of the vegetative only cover) will reduce the amount of seasonal freezing of the tailings. The reduction occurs because of the insulating nature of the covers and as a result of decreasing the evapotranspiration heat loss during summer months. The vegetation only cover will tend to increase evapotranspiration losses and increase heat losses from the soil.

The engineered covers almost completely eliminate seasonal freezing of the tailings soil. The barrier and subdrainage system is, however, subjected to seasonal freezing and thawing. The drain would freeze seasonally. Spring runoff would be essentially complete before the drain and barrier thawed.

The rock cover limits freezing of the tailings. A vegetated cover has little no influence upon the depth of freezing.

8.4.3 THAW CONSOLIDATION

Ice rich frozen soil settles upon thawing. Winter tailings deposition results in freezing of the tailings in thin layers which are subsequently covered with more frozen tailings. In the summer the frozen tailings are covered with insulating layers of thawed tailings. Consequently, the frozen tailings do not get a chance to thaw as they would in an inactive area. Upon decommissioning, the frozen tailings will slowly thaw and consolidate. The amount of settlement depends upon the excess ice content of the frozen soil. At Rabbit Lake, it is estimated that the ice content of frozen tailings is sufficient to result in 3.5 m of settlement upon thaw over a 15 m thickness of frozen tailings.

The rate of settlement depends upon the rate of thawing and upon the drainage capability of the soil. For typical tailings characteristics and thawing rates at all the sites investigated, the rate of settlement will be almost completely controlled by the rate of thaw. At the Rabbit Lake site it is estimated that complete thaw may take upwards of 100 years. At the other sites, the estimated time for complete thaw of the tailings is 10 to 20 years.

Thaw consolidation theory is quite well developed and reliable. The data requirements consist of oedometer thaw strain tests carried out on representative frozen core samples. The thaw strain tests will provide the amount of settlement that can be expected upon thaw as well as the consolidation rate characteristics of the thawed soil. A proper thermal analysis is required to estimate the rate of thaw.

8.4.4 FROST HEAVE

8.4.4.1 General

Heave of the tailings during seasonal freezing is of concern because:

- heave could distort the tailings surface and disrupt the surface drainage, and
- there is a potential for successive freeze-thaw cycles to transport pore fluid to the surface.

Heave features have been observed at Gunnar and Key Lake that are of such magnitude to disrupt a decommissioned drainage surface. The frost pumping scenario is speculative, but because of the potential for mass transport of fluid from depth to surface, it requires assessment.

There are two fluid transport mechanisms resulting from frost action:

- the frost heaving process whereby freezing attracts water towards the freezing front, and
- pore water expulsion whereby water is expelled from the freezing front.

8.4.4.2 Segregational Heave

Frost heave has been a concern for many years in civil engineering applications such as roadways and structures. In the last 15 years, it has been the object of considerable research with respect to chilled gas pipeline design.

Frost heave is the accumulation of moisture as ice at the freezing front during soil freezing. The conditions necessary for frost heave to occur are:

- freezing temperatures,
- available moisture, and
- frost susceptible soil.

Frost heaving consists of two processes:

- freezing of in situ moisture which results in a 9 percent volume expansion of the soil water, and
- freezing of free moisture which migrates to the freezing front and forms ice lenses.

The heave associated with ice lensing can be considerably more than that associated with in situ freezing.

As the freezing front advances into a frost susceptible soil, suction pressures in the water phase are developed. The suction pressures draw free water toward the freezing front where it freezes into ice lense and results in volume expansion or heave of the soil. The direction of heave is always parallel to the direction of heat flow. The water phase suction is developed by capillarity action much the same way as capillarity in unfrozen, unsaturated soils.

The heaving process is therefore a coupled thermal and hydraulic process (EBA 1979). Heave is limited both by the thermal capacity to freeze the soil (heat flux) and by the availability of water at the freezing front (fluid flux). It is the coupling of the heat and moisture flow processes that results in the rhythmic ice lensing, or formation of a series of ice lenses within a freezing soil. When the availability of water exceeds the heat removal rate, an ice lense continues to form at the freezing front. When the heat removal rate temporarily exceeds the availability of water, the freezing plane advances to a position where the supply of water is more favorable. The process repeated generates a series of frozen soil and ice layers.

The water supplied to the freezing front can come from two sources:

- a reservoir at depth, and
- consolidation of soil adjacent to the freezing front.

The intervening soil layers can thus be overconsolidated by the freezing process. In this case, much of the excess water may be readsorbed by the soil upon subsequent thaw.

In uranium tailings, all the conditions necessary for frost heave are present. First, freezing temperatures for a considerable depth are present. Second, there is ample available water. The water table in tailings deposits is near surface and, even in the underdrained case of Key Lake, the moisture content of the tailings is sufficiently high so as to provide water for heaving. Third, the tailings are sufficiently fine grained so as to be frost susceptible. Finally frozen tailings quite often are buried by subsequent tailings depositon. This has happened at Rabbit Lake and at Beaverlodge.

Frost heave theory is quite well developed, however, application of the theory is still in the developmental stage. The data requirements consist of a credible thermal analysis in conjunction with frost cell testing. The frost cell testing consists of freezing a soil sample in the laboratory and observing the rate of heave and the amount of water drawn to the freezing front.

The frost heave was estimated at each of the tailings sites for various cover conditions. The results are summarized in Table 8.4-2.

TABLE 8.4-2
SUMMARY ESTIMATED SEASONAL HEAVE

SITE	COVER (m)	FROST DEPTH (m)	WATER INTAKE (mm)	SEGREGATED HEAVE (mm)	IN SITU HEAVE (mm)	TOTAL HEAVE (mm)	ICE SEGREGATION RATIO (%)
Gunnar	0	2.2	190	210	80	290	13
	1	2.44	130	140	50	190	
	2	2.83	77	85	30	115	
Key Lake	0	1.3	305	332	90	421	32
	1	1.74	175	190	55	245	
	2	2.30	80	90	25	115	
Rabbit Lake	0	2.1	428	470	130	600	22
	1	2.51	300	325	95	415	
	2	3.0	190	210	60	270	
Gunnar - continuous freezing to 5 m (3 years)							
	0	5	425	460	175	635	12

NOTE: Calibrated to first thermal analysis for each site from Chapter 4.0 of (SRK 1987) (Normal temperature, wind and snow)

The estimated heave and resulting ice segregation ratios correlate quite well with the observed ice segregation ratios estimated from photographs of frozen Key Lake tailings (Knight and Piesold 1986). The estimated heave at the Gunnar frost boils also relates favourably to the observed amount of heave.

The effect of a cover is twofold. First, the cover insulation limits freezing of the tailings and thus limits heave. Secondly, the surcharge provided by the cover will reduce the amount of heave. The potential for heave of a full 2 m thick engineered cover is nominal.

8.4.4.3 Pore Water Expulsion

Freezing can also expel water from the freezing front. This phenomenon has been described by others (Tsytovich 1975, MacRoberts and Morgenstern 1975 and Arvidson and Morgenstern 1977). The implications of this mechanism to uranium tailings is that the excess pore water pressures generated by freezing can locally rupture the ground surface and form frozen mounds or boils. This process is similar to the accepted of genesis of pingos in the McKenzie River Delta area (Anderson and Andersland 1978).

Pore water expulsion from a freezing soil occurs when:

- the total stress at the freezing front is high,
- the rate of freezing is high, and
- in coarse grained soils.

When the propensity for moisture attraction is at the freezing front is overcome by any or a combination of the above factors, the volume change on freezing forces unfrozen moisture away from the freezing front. Although the occurrence and physics of this phenomenon have been well documented, there is little information available on when pore water expulsion can be expected to occur. The effect of grain size and stress on the pore water flow resulting from open system freezing of three soils has been investigated in the laboratory, (Arvidson and Morgenstern 1977). For coarse grained Ottawa sand, pore water expulsion occurred for all effective stresses. For Devon silt, and modified Devon silt (modified Devon silt had a higher silt content), pore water expulsion occurred at applied stresses greater than 70 and 215 kPa respectively. The pressure above which pore water expulsion occurs is termed the shut-off pressure.

Frost mounds of about 1 to 1.2 m in height on the Key Lake tailings impoundment have been reported (Knight and Piesold 1986). The mounds had a very irregular topography and a ruptured and cracked surface. The height of the mounds is too great to attribute to ice segregational heave. They are therefore believed to result from the pore water expulsion mechanism. The gradation of the Key Lake tailings, however suggests that ice segregation rather than pore water expulsion would occur. The moisture content of the tailings is much greater than the moisture content of any available laboratory heave testing. It is expected that high moisture content tailings are more likely to experience pore water expulsion than drier soils of similar gradation for which pore water expulsion data are available.

The technology for prediction of when pore water expulsion might occur is quite well developed in a qualitative sense. However, limited data exists to apply to a tailings scenario. Considerable work needs to be done before one can predict when and where pore water expulsion features are likely to occur. From the Key Lake experience, it would appear this heave mechanism is probable near open water and where a relatively impermeable (frozen) layer exists at shallow depth.

8.4.4.4 Pore Water Pumping

Frost pumping is a process whereby successive seasonal freezing can transport fluid from depth to the surface. To our knowledge this process has not been studied within the literature or observed in the field. As such, the existence of the process is speculative.

As discussed in the previous section, frost heave can result in significant (200 mm) amounts of water being drawn toward the freezing front. As the soil thaws from the surface, this fluid would be liberated. Downward flow would be blocked by frozen soil and upward flow could occur as the tailings consolidate. As an upper limit, the potential for frost pumping is equal to the amount of segregational heave. The net effect of seasonal freezing would then be to successively "pump" pore water from depth to the surface.

The source of water for segregational heave is not clear. Some undoubtedly comes from free water at depth. Some also comes from consolidation of the soil adjacent to the forming ice lense. If the soil is quite incompressible, then flow from depth would be favoured. However, if it is compressible, then consolidation of the adjacent soil is likely favoured.

Should flow arise from consolidation of adjacent soils, then upon subsequent thaw, deliberated water may be readsorbed by the soil and not be free to flow towards surface. Should readsorbtion by adjacent soil layers be the dominant mechanism, then frost pumping is not likely to occur.

8.4.5 EFFECTS ON PERMEABILITY

Freeze thaw action will increase the permeability of earth structures or covers. If the soil subjected to freeze thaw is unsaturated, freezing will shrink the soil and induce cracking. This mechanism is routinely observed in highway subgrades. The shrinkage results in cracking of the soil and a large increase in secondary permeability.

If the soil is saturated, freezing will result in some ice segregation within the soil. Upon thaw, the discontinuities formed by the ice segregation do not completely heal and a secondary soil structure is developed. The structure will increase permeability.

The amount of permeability increase is difficult to estimate. Based upon the observed differences in permeability in weathered and unweathered clay strata in Southern Saskatchewan, an increase in soil permeability of one order of magnitude as a result of frost action is reasonable.

8.4.6 SOIL EROSION

The major mechanism for frost induced soil erosion is the pore water expulsion frost boils. The heave of these features is so severe that the soil at the apex of the boil would crack and be exposed to wind erosion.

8.5 ACID GENERATION

8.5.1 GENERAL

Acid generation is a common concern for many mining operations. The NUTP have undertaken several studies (SENES 1984, Beak 1985, Hester 1985, SENES et al 1986) greatly improving the state of knowledge on factors affecting acid generation in mine tailings.

This sub-section of the manual addresses the effects of tailings management alternatives on the acid (sulphate) generation flux of pyritic tailings. Flux is defined as the molar amount of sulphate generated from sulphidic solids per unit tailings surface area in a prescribed time period. Flux is dependent on a number of variables including the reactivity of the solids, the diffusivity of the oxygen through the tailings and the depth to the water table.

8.5.2 THE REACTION ZONE

In pyritic tailings, it is useful to distinguish between an oxygenated (i.e. oxidizing) zone near the surface and a redox zone below (SENES 1984). The oxidizing zone comprises that portion of the tailings which is in contact with atmospheric oxygen. Usually, this zone is located in the hydraulically unsaturated region (vados layer), where the diffusive transport of oxygen is significant. The redox zone is situated immediately below the oxidizing zone. In this anoxic region, the oxidized species exported from the oxidizing zone may undergo some chemical redox reactions. It is the chemical and biological events in the oxidizing zone that largely determine the quality of the groundwater, while redox reactions play a somewhat secondary role.

The oxidation of pyrite in the oxidizing zone can be expressed by the following reaction:

$$2\,FeS_2 + 7\,0_2 + 2H_20 \rightarrow 2\,Fe^{2+} + 4\,S0_4^{2-} + 4\,H^+ \qquad (8.5.1)$$

In an aerobic environment, the ferrous ion is thermodynamically unstable and undergoes oxidation to the ferric (Fe^{3+}) state by the following reaction:

$$2\,Fe^{2+} + 2\,H^+ + 1/2\,0_2 \rightarrow 2\,Fe^{3+} + H_20 \qquad (8.5.2)$$

Reactions (1) and (2) can be catalyzed by chemolithotrophic bacteria, particularly Thiobacillus ferrooxidans, or proceed abiologically. In the absence of bacterial activity, the reaction (2) is slow at low pH values (below pH = 3.5), thus the ferrous ion does not oxidize to the ferric state (Brierley 1978). In the presence of Thiobacillus ferrooxidans, the oxidation of the ferrous ion proceeds rapidly. Elevated ferric to ferrous ion ratios in tailings porewater at low pH values is a strong indicator, albeit not an absolute proof, of biological activity in the tailings mass.

A significant portion of the acidity, however, does not result from the direct oxidation process indicated above. It can be shown that both the hydrolysis and the precipitation of the ferric ion as ferric hydroxide or jarosite can contribute substantially to the net acidity:

$$\begin{aligned}
Fe^{3+} + H_20 &\rightarrow Fe(OH)^{2+} + H^+\\
Fe^{3+} + 2\,H_20 &\rightarrow Fe(OH)^{+}_{2} + 2H^+\\
Fe^{3+} + 3\,H_20 &\rightarrow Fe(OH)^{\circ}_{3}\,(aq) + 3H^+ \qquad (8.5.3)\\
Fe^{3+} + 3\,H_20 &\rightarrow Fe(OH)_3\,(s) + 3H^+
\end{aligned}$$

Depending on the extent of the above reactions, the net acid generation can range between 2.0 and 4.0 hydronium ion (proton) equivalents.

Under both biological and non-biological conditions, the oxidative reactions in the tailings are conveniently expressed in terms of a sulphate generation flux. It should be noted, that metal ion concentrations, for example, ferric ion, can be subject to solubility equilibrium constraints. Since solubility is often the function of pH and the ionic strength, the concentration of these metal ions in solutions may not be directly related to the rate of pyrite oxidation.

8.5.3 SULPHATE GENERATION FLUX/OXYGEN DIFFUSION

As indicated above, sulphate production takes place predominantly in the oxidizing zone where the diffusive transport of atmospheric oxygen is significant. Assuming that the tailings are homogeneous with respect to physical (temperature, moisture content, particle size), chemical (pyrite content, reactivity), and transport (oxygen diffusivity) parameters, the sulphate generation flux in the tailings is related to the thickness of the oxidizing zone λ and the reactivity of the pyrite (R_s) as follows (Halbert et al 1983):

$$N_s = \lambda R_s \rho_T \qquad (8.5.4)$$

N_s = sulphate generation flux (moles/m^2/year)
λ = thickness of the oxidizing zone (m)
R_s = reactivity of the tailings (moles sulphate produced/kg tailings/year)
ρ_T = density of tailings (kg/m^3)

Oxygen is generally regarded as the limiting reactant in the tailings (SENES 1984). It can be shown that the transport of oxygen into the tailings pore space by barometric and hydraulic "pumping" is negligible, hence the primary mechanism of oxygen transport is diffusion. This diffusive transport approaches steady state in a relatively short time period (less than 10 days), consequently the diffusive transport can be expressed by the following second order differential equation:

$$D_e \frac{\partial^2 C}{\partial z^2} = \frac{3.5}{2} \rho_T R_s \qquad (8.5.5)$$

where:

De = the effective diffusivity of oxygen through the tailings (m^2/year)
C = concentration of oxygen (moles/m^3)
z = distance into the tailings (m)
ρ_T = bulk density of tailings (kg/m^3)
R_s = pyrite reactivity (moles sulphate formed/kg tailings/year)

The constant term (3.5/2) results from the stoichiometry of pyrite oxidation. Pyrite reactivity (R_s) is dependent on oxygen concentration. However, the reaction rate is near zero order with respect to oxygen to very low concentrations (~0.45 moles/m^3 in the gas phase [Myerson 1981]). In this case, the oxygen concentration gradient at the tailings surface is given by (Halbert et al 1983):

$$\left.\frac{C}{z}\right|_{z=o} = - \left(\frac{3.5 R_s}{D_e} \rho_T C_o\right)^{0.5} \qquad (8.5.6)$$

Where

C_o = concentration of oxygen at the tailings surface (moles/m^3)

Once the concentration gradient at the surface is known (equation 6.10.6), the thickness of the pyrite oxidation zone λ can be readily calculated:

$$\lambda = - \frac{2}{3.5} \frac{De}{R_S \rho_T} \left.\frac{\partial C}{\partial z}\right|_{z=o} \qquad (8.5.7)$$

Combining equations (8.5.6) and (8.5.7) and substituting into equation (8.5.4), the flux of sulphate generation is given by:

$$N_s = \left(\frac{4}{3.5} D_e C_o \rho_T R_S\right)^{0.5} \qquad (8.5.8)$$

The most important feature of equation 6.10.8 is that the diffusive transport of oxygen and tailings pyrite reactivity are of equal significance with respect to the sulphate generation flux. The terms most likely to be modified by tailings management are the effective diffusion coefficient of oxygen (D_e) and the reactivity of the pyrite (R_s). It should be noted, that the flux is proportional to the square root of the respective terms. Thus, hundred-fold changes in the diffusivity of oxygen or pyrite reactivity would cause about ten-fold change in the sulphate flux. The factors that control these two important parameters are discussed below.

8.5.4 DIFFUSIVITY OF OXYGEN

In the unsaturated zones of pyritic tailings, the diffusive transport of oxygen through the gas-filled pores controls the oxidation rate. The effective diffusivity coefficient of tailings (D_e) is a non-linear function of the air-filled porosity (E_a) and can be expressed functionally as follows (Reardon and Moddle 1985):

$$D_e = 630\left(\frac{E_a - 0.05}{0.95}\right)^{1.7} \quad (\mathrm{m}^2/\mathrm{year}) \qquad (8.5.9)$$

Since the total porosity (E) is the sum of the air-filled and water-filled porosities, it is evident, that the diffusivity coefficient declines rapidly with the moisture content. The total porosity of the tailings is usually in the order of 0.45 m^3/m^3, while the bulk density ranges from 1.2×10^3 kg/m^3 to 1.8×10^3 kg/m^3, 1.4×10^3 kg/m^3 being typical. At a moisture content of 10%, for example, the effective diffusivity coefficient is approximately 90 m^2/year, while at 25% moisture content is about 4 m^2/year.

Although not evident from equation 8.5.9, the diffusivity coefficient reaches a minimum value when the pore space is completely occupied by water. In flooded tailings, the diffusivity coefficient is in the order of 0.05 - 0.10 m^2/year. Thus, the diffusivity coefficient may decline by three orders of magnitude if the tailings are under water cover. This would correspond to some thirty-fold decrease in the sulphate generation flux.

A study of tailings deposited in Mandy Lake, Manitoba, (Hamilton and Frazer 1978) provide a good example concerning the effect of water cover. Highly reactive, sulphidic copper tailings have been deposited some thirty-five years ago in a shallow lake. The tailings under water have not undergone oxidation to any significant degree. Only along the shoreline, where the tailings were presumably exposed to atmospheric oxygen, was evidence of sulphate generation and pH decline to 4.5. In contrast, unsaturated tailings of similar composition, deposited on land, have become highly oxidized with characteristic pH values between 2 and 3. The authors observed evidence of revegetation and healthy benthic community, while no vegetation developed on the dry tailings. The Buttle Lake tailings disposal site has been studied by B.C. Research (1974, 1980, 1986). Core samples of tailings from the bottom of this lake have showed no evidence of significant oxidation. The tailings deposits have been estimated to contribute no more than 10% to the total heavy metal load to this oligotrophic, soft water lake of limited assimilation capacity. In 1980, Buttle Lake water was safe to drink and the metal content of fish flesh was well below allowable limits.

8.5.5 TAILINGS REACTIVITY

The site specific variability of sulphide tailings, both physical and chemical, precludes accurate assessment of the reactivity without experimentation and monitoring. It is well-known, that substantial differences in oxidation rates exist. Some of these are inherent properties of the minerals. For example, pyrhhotite, marcasite, and framboidal pyrite are all more reactive than pyrite (Steger and Desjardins 1978). Similarly, the reactivity of base metal sulphides is mineral specific, although the magnitude of the solubility product (K_{sp}) has been suggested as a qualitative measure of the reactivity (Tributsch and Bennett 1981). Larger K_{sp} values imply higher reactivity.

The pyrite content and the specific surface area of the sulphidic minerals have been frequently identified as important factors with respect to pyrite oxidation. Since the tailings are usually unconsolidated material, sulphides occur as distinct particles with size distribution not unlike the tailings as a whole. Since most oxidative reactions take place on the surface of the minerals, these tailings particles shrink in size as the reactions proceed. As the smaller particle size fraction completely dissolves, the reactivity of the tailings declines continuously. Depyritization of the tailings offers one alternative in controlling acid generation (SENES 1983). Depyritization itself, however, is not a particularly efficient means of reducing the sulphate generation flux. A 90% reduction of the pyrite content would cause no more than 67% reduction in the sulphate generation flux if the entire tailings mass is depyritized. Partial depyritization is even less effective. A depyritized cover, however, provides secondary benefits by reducing tailings temperature and raising the water table.

The net reactivity of the pyritic material is assumed to be the sum a biological process, mediated by bacteria, and a chemical oxidation process. The bacterium, Thiobacillus ferrooxidans has been widely regarded as the most active iron and sulphide sulphur oxidizer in tailings and waste rock. In the Elliot Lake region, the first evidence of bacterial activity associated with the uranium ores was found (Harrison et al 1966a, 1966b). In subsequent years, this region has proven to be a rich source of iron and sulphur oxidizing bacteria. Altogether five strains of T. ferrooxidans (Dispirito et al 1982) and two strains of T. acidophilus (Guay and Silver 1975, Dispirito et al 1982) have been isolated at various locations. The chemical and the biological reaction sequences are virtually indistinguishable. Bacteria act primarily as catalysts without affecting the thermodynamics of the reactions. As any biological system, however, bacteria are more sensitive to environmental changes than chemical reactions.

The reaction temperature is one of the most important variables affecting pyrite oxidation. Both the biological and the chemical oxidation rates are temperature dependent. This dependency is best expressed by an Arrhenius-type equation (SENES et al 1986). In pyritic tailings, the activation energy is in the 25.6 kcal/mole in case of biological oxidation (Halbert et al 1983) in comparison to 13.3 kcal/mole during chemical oxidation of pyrite. This corresponds to approximately 4.5 fold increase during biological and two fold increase in chemical activity for each 10°C increase in temperature. At 4 C, the biological and chemical activities are virtually identical. At 30°C, the biological activity becomes over an order of magnitude higher than the chemical activity. In tailings, therefore, the biological activity during the summer and early fall may account for most of the sulphate production, particularly if the porewater pH and moisture content favour bacterial colonization.

The reactions product heat, thereby maintaining activity during cold weather. There is some evidence that older tailings piles can reach 45°C and even 55°C once the role of Thiobacillus ferrooxidans is taken over by an unidentified thermophilic bacteria.

The pH effect on biological pyrite oxidation can be expressed as follows (SENES et al, 1986):

$$R_s \; \alpha \; \left(\frac{1}{1 + 10^{2.5-pH} + 10^{pH-4.0}}\right) \qquad (8.5.10)$$

The above expression is structurally identical with pH effects on enzyme kinetics (Bailey and Ollis 1986). Maximum biological activity occurs at pH of 3.25. The reaction rate declines rapidly at alkaline pH values (Arresteyn 1979, 1980).

The pH effects on chemical oxidation of pyrite are less significant. The following pH dependent expression for a biological pyrite oxidation has been developed (Smith and Shumate 1970):

$$R_s \; \alpha \; (pH)^{0.7} \qquad (8.5.11)$$

In contrast to the biological oxidation rate, the chemical oxidation increases with increasing pH value. However, the greater pH decline of the biological oxidation imparts a significant benefit by maintaining a near neutral pH value. This is best accomplished by adding limestone to the tailings. By limestone addition, the pH may be buffered at pH of 7.2. At this pH, the biological activity is negligible (0.20% of the optimum value) and the chemical oxidation of pyrite is the only significant factor.

Both the biological and the chemical oxidation of pyrite require moisture. Oxidation rate appears to increase linearly with water content until hydraulic saturation is reached (Brock 1975). It has been shown in the previous section that the diffusivity of oxygen decreases with moisture content. The combination of these apparently opposing tendencies result in a net decrease of the pyrite oxidation flux.

The effect of the moisture, expressed as water-filled porosity on the relative sulphate generation flux is illustrated in Table 8.5-1.

TABLE 8.5-1
WATER CONTENT EFFECTS ON ACID GENERATION

Water Filled Porosity (m^3/m^3)	Relative Sulphate Generation Flux (%)
0.0	100
0.10	100
0.15	96
0.20	95
0.30	91
0.35	41
0.40	0

As shown above, the sulphate generation flux reaches a broad maximum value for water filled porosities ranging from 0.1 to 0.30 and declines rapidly above. This suggests that the most efficient means of lowering the acid generation flux is by raising the water table in the tailings. If "h" is assumed to be the distance to the water table, it can be shown that the relative sulphate generation flux is given by (approximately) as follows:

$$\mathrm{Flux}_{\mathrm{Rel}} = \frac{h}{\left(\frac{4\ \mathrm{De\ Co}}{3.5\ R_s\ \rho_T}\right)^{0.5}} \qquad (8.5.12)$$

It can be shown, that reducing the distance to the water table to 1 m or less would result in at least 90% decrease in the sulphate generation flux. In fact, increasing the water table is the most efficient and practical method of reducing the acid production flux (Halbert et al 1983).

8.5.6 CONTROL TECHNOLOGY

To illustrate the use of the sulphate generation flux for the assessment of control technologies, assume that some hypothetical, pyritic tailings contain about 5% pyrite (FeS_2). The tailings are unsaturated and the pyritic sulphur oxidizes at an in-situ rate of 0.005 moles FeS_2/kg/year. The moisture content and the pH conditions (pH of 3.25) are at optimum for biological activity. Chemical oxidation would account to approximately one-fifteenth of the total oxidation, i.e. 1 mole FeS_2/m^3/year. By stoichiometry, the tailings would possess a "total" reactivity of 0.01 moles sulphate/kg/year of which 0.33×10^{-3} moles sulphate/kg/year is associated with biological activity. Furthermore, assuming that the tailings have a bulk density of 1,400 kg/m^3 and a total porosity of 0.45, the water content is 15, the diffusivity coefficient of oxygen is calculated to be 40.8 m^2/year. Conditions described above is regarded as the baseline for subsequent evaluation.

The sulphate generation flux is calculated using equation 8.5.8. This flux would be 76.65 moles of sulphate/m^2/year. At an annual net precipitation of 0.5 m/year, this flux would be equivalent to 15,330 mg/L sulphate concentration in the porewater.

The first close-out option to be considered is to provide a waste rock cover. The primary consequence of this management option is the reduction of the annual summer temperature in the tailings. A net reduction of 4°C would give a sulphate generation rate of 6×10^{-3} moles/kg/year. This rate is equivalent to a sulphate generation flux of 59.37 moles SO_4^{-2}/m^2/year and a porewater sulphate concentration of 11,400 mg/L. If the cover increases infiltration and moisture content, the rate would be further reduced.

A closeout option with depyritized tailings would lower the temperature as well as raise the water table. Let us assume that 2 m of depyritized tailings are deposited on the pyritic tailings. Such a cover would lower the tailings temperature by 6°C and raise the water table by approximately 2.0 m. Assuming a water content of 20%, the sulphate generation flux would be reduced to 21.06 moles SO_4/m^2/year and porewater concentration of 2,021 mg SO_4/m^2/year. A significant improvement would be achieved if limestone is added to the depyritized tailings. If the pH after limestone addition is maintained at pH = 7.2, the sulphate generation flux would become 7.9 moles SO_4/m^2/year (sulphate concentration 758 mg/L).

The results of the above calculation are summarized in Table 8.5-2.

TABLE 8.5-2
EFFECT OF CLOSEOUT OPTIONS ON ACID GENERATION

Tailings/Cover	Depth (m)	Sulphate Flux (moles/m^2/year)	Reduction of Acid Flux (%)
None	-	76.65	-
Waste Rock	0.6	59.37	22.5
Depyritized Tailings	2.0	21.06	72.5
Depyritized Tailings + Limestone	2.0	7.9	89.7

It is important to note that the above example is used as illustration only. Nevertheless, the example gives a relative measure of acid reduction with various alternatives.

If tailings are frozen or saturated, oxidation occurs at very low rates and would not produce acid conditions. Therefore any remedial action which produces a condition where tailings are frozen or water covered will very likely prevent acid generation.

As noted above, covers are effective but only eliminate acid generation when the water table rises into the cover. Figure 8.5-1 developed from the RATAP model illustrates the effects of depth of earthen cover (glacial till) on a typical Elliot Lake tailings area for various depths of unsaturated tailings. As shown on the Figure, tailings with a 500 mm unsaturated zone would initially produce about 50% as much acid as those with a 2.5 metre oxidizing zone. Two metres of the cover over these tailings would reduce the oxidation rates by 60 and 70 percent respectively. Greater reductions would occur if the water table was to rise as a result of cover addition. It is worthy to note that the depth of the unsaturated zone is often not a major factor in determining the initial acid generation rate. This is because oxygen depletion occurs in the near surface zone thus being the rate limiting factor. However, the deeper the unsaturated zone, the longer acid generation will continue. Eventually, virtually all pyrite would be oxidized from the unsaturated zone.

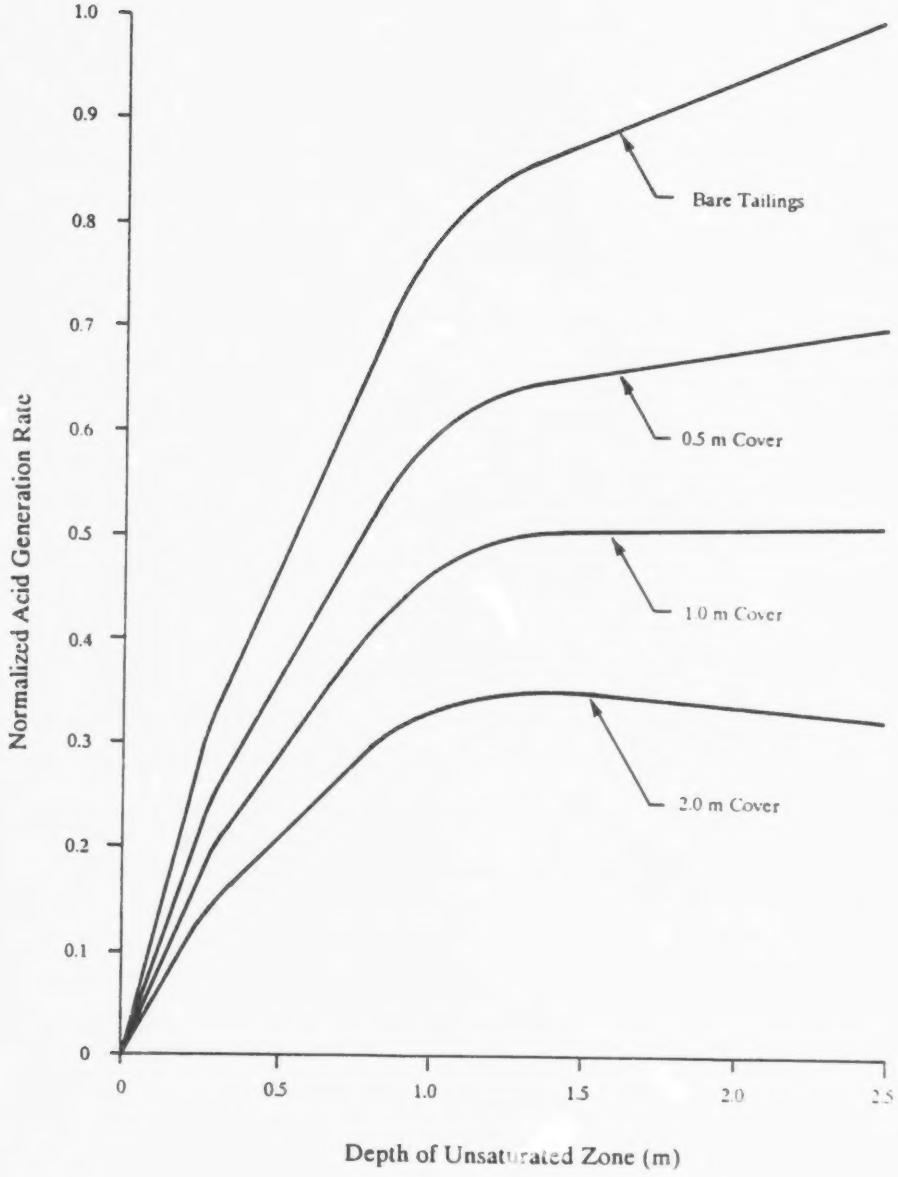


Figure 8.5-1 The Effects of Till Cover on Acid Generation Rates

CHAPTER 9.0
SURVEILLANCE AND MONITORING

9.1 GENERAL

In the final stages of closing a uranium mine/mill facility, various types of surveillance are undertaken, the primary purpose of which is to ensure the success of reclamation activities. The primary objectives for long-term tailings disposal is to ensure public health and safety and minimize the release of radioactivity to the environment. Other forms of contamination release, most notably elevated acidity levels, also warrant surveillance.

The information upon which assessments of the adequacy of tailings disposal methods are based comes from monitoring. Surveillance includes inspection and monitoring with the purpose of establishing compliance with standards or objectives, and is conducted during the operational and post-operational phases of activity (the latter including both the periods of decommissioning and reclamation and the five-year (or longer) transitional phase which precedes abandonment and the commencement of institutional control. Monitoring, on the other hand, has been classified into:

- pre-operational,
- operational,
- post-operational (short-term) - transition period, and
- post-operational (long-term).

Pre-operational monitoring is carried out by the (prospective) operator at a site, since the data are submitted in support of applications to construct, conduct underground exploration, remove ore or, ultimately, to decommission. Pre-operational monitoring data form the major part of the baseline environmental survey (see Section 9.2). The operational monitoring program should have four goals, (U.S. Nuclear Regulatory Commission 1980a):

- demonstrate or confirm compliance with applicable standards and regulations,
- evaluate adequacy and performance of containment control systems and procedures,
- evaluate environmental impacts of operation and provide an early warning of potential impact prior to the creation of an irreversible situation, and
- begin the evaluation of long-term trends and the potential buildup of concentrations of substances of concern in the environment.

Post-operational or transition phase monitoring is implemented immediately following the completion of reclamation activities to determining compliance with objectives during the transitional phase. Long-term monitoring forms part of institutional control and is less intensive and more selective than in the earlier stages.

9.2 PRE-OPERATIONAL MONITORING AND BASELINE ESTABLISHMENT

The establishment of a set of baseline environmental data must be undertaken by monitoring during the pre-operational stage of a uranium mine/mill facility. The recommended minimum period during which measurements should be taken is one year prior to the beginning of any type of site activity such as land clearing or drilling (U.S. Nuclear Regulatory Commission 1980b). In Canada baseline data collection is usually carried out during the exploration phase of a project. For measurements of physical and/or chemical processes which may be subject to annual variations, a longer period (two or more years) is recommended (Environmental Protection Service 1978). As noted above, the results of these measurements can then be used as reference levels during surveillance of decommissioning and remedial activities. Canadian practice is similar with minimum requirements of one year's baseline monitoring.

The terms "baseline" and "background" can be interpreted differently. Baseline levels refer to those derived from pre-operational monitoring data. This appears to be the most common interpretation. Such levels may be true natural background levels or may reflect contamination stemming from some other source such as nearby mining facilities.

TABLE 9.2-1
RADIOLOGICAL SAMPLING[1] - PRE-OPERATIONAL MONITORING

	Typical[2] Data Collected						
Media[3]	radon	gamma	uranium	thorium isotopes	radium 226	lead 210	polonium 210
Air	♦						
Suspended Particulate			♦	♦	♦	♦	
Surface water			♦	♦	♦	♦	♦
Groundwater			♦	♦	♦	♦	♦
Sediment			♦	♦	♦	♦	
Soil		♦	♦	♦	♦	♦	
Vegetation			♦	♦	♦	♦	♦
Aquatic Life			♦	♦	♦	♦	♦
Mammals			♦	♦	♦	♦	♦

[1] data modified from EPS (1978) and NRC (1986).

[2] this list is not exhaustive. Specific plants, mammals and fish that are part of the human food chain are candidates for sampling. Other plant and animal species may be monitored because they are good radiological indicators.

[3] see Table 9.4-1 for the relative importance of the media.

A comprehensive set of baseline radiological (pre-operational) data will include radioisotopic content analyses of the items listed in Table 9.2-1. Monitoring of certain non-radiological constituents, specifically trace metals, should be conducted in parallel with the radiological monitoring program. This serves to establish background levels of these elements whose concentrations in the environment may increase owing to their concentration in the ore and/or to milling processes, and the consequently elevated levels in tailings.

The media and measurement types listed in Table 9.2-1 would not form a comprehensive list of baseline data; many other chemical and biological parameters may require consideration.

Saskatchewan Environment (1980) has prepared "General Guidelines for the Preparation of an Environmental Impact Statement." This report contains a thorough listing of the baseline data collection requirements.

9.3 POST-OPERATIONAL MONITORING AND SITE INSPECTION

The requirements agreed upon between the licensee and the regulatory agencies regarding close-out of a mine/mill facility are highly site-dependent. The terms and conditions under which a mine site is decommissioned and reclamation takes place are described in individual plans submitted by licensees and in the approvals granted by the AECB. For these reasons, a generic set of post-operational monitoring and inspection tasks has limited applicability for any specific case. It would appear, from case studies of decommissioned uranium mines in Canada, i.e. Beaverlodge, Madawaska and Agnew Lake, that site inspection is an ongoing process during decommissioning. Nonetheless, for the purpose of establishing a reference level of conditions to which long-term monitoring results can be compared, and to ensure compliance with close-out requirements, site inspections would be expected to comprise the aspects outlined below.

Upon completion of all reclamation activities, an on-site inspection should be undertaken to verify that all planned works have been successfully completed under the terms of the Approval. These would include the dewatering, removal, displacement or contouring of tailings, the application of covers, the construction or destruction of containment structures and any alteration of levels in water bodies. A permanent record of these features can be provided at minimal cost by aerial photographic survey, as is recommended in the U.S. (DOE 1986c). Multi-scale black and white vertical airphotos accompanied by large-scale infrared airphotos can be used to document the initial physical integrity of the reclaimed tailings site as well as the extent and health of the vegetative cover.

Since a monitoring program forms an integral part of Decommissioning Approvals and will have been in place at least since the operational phase, the data collected up to the time of completion of reclamation activities should also be assessed. Should the objectives be exceeded, monitoring thereafter will be geared toward verifying compliance and, if warranted, an investigation into possible remedial action should be undertaken.

After the initial site inspection, the timing of subsequent inspections will be dictated by the demonstrated success of reclamation activities, i.e., if it is confirmed by monitoring data that levels of environmental radioactivity are decreasing as predicted, further surveillance activities may only be required once-yearly during the transitional phase. Post-operational monitoring, however, should be conducted at the frequency specified in the Approval.

9.4 MONITORING PROGRAM

9.4.1 GENERAL

The goal of an environmental and radiological monitoring programs are to evaluate on an ongoing basis the effects on human health and the environment. Data must be gathered to:

- assess doses to critical groups,
- assess collective doses,
- assess the significance of potentially important pathways,
- define long-term trends and accumulation,
- correlate releases and environmental levels; build environmental models and validate them, (or UTAP model) and
- assess effects on biota.

The four basic considerations that go into the design of a program are the critical pathways, critical radionuclides, critical population groups and sampling methodology. The latter will involve technical and logistical considerations such as the types of sample and measurement, their frequency and location and sensitivity requirements.

Priorities can be assigned among the various monitoring media according to their significance as pathways to human exposure, in terms of dose and long-term impact (Table 9.4-1). The rationale behind the ranking must also discriminate between measurement types on the basis of their reliability as indicators of human exposure and environmental impact. Depending on specific site conditions, the example shown in Table 9.4-1 may contain irrelevant monitoring media. Food crops, for example, are not an important ingestion pathway in remote northern regions and atmospheric deposition may not be attributable to tailings where no sub-aerial surface erosion occurs, e.g. submerged tailings.

TABLE 9.4-1
RANKING OF MONITORING MEDIA

(5 = highest rank; 1 = lowest)

Atmospheric	Terrestrial	Aquatic	Rank
Radon*		Surface water Drinking water	5
Airborne particulate matter External Radiation		Fish	4
	Edible and non-edible vegetation Food crops	Groundwater	3
	Meat and animal produce Soil	Aquatic plants Sediment	2
Ground Deposition		Invertebrates Waterfowl	1

(Modified after Environmental Protection Service 1978)

* May be top high for Canada

The NUTP office has prepared a sampling manual for monitoring data collection which thoroughly addresses sampling methodology and procedures (Golder Associates and SENES Consultants 1985).

9.4.2 SURFACE WATER

Surface waters are commonly used as drinking water supplies and therefore represent critical pathways to human exposure. Monitoring during the pre-operational and post-operational phases should be directed towards: (a) onsite or offsite impoundments that may be subject to drainage from potentially contaminated areas, or that could be affected by the failure of a tailings containment structure; (b) surface waters passing through or sufficiently close to the tailings area that could be affected by the same processes. During the operational phase, tailings pond effluent and retention pond monitoring is conducted regularly as part of the facility operations. Monitoring of final effluent at its point of release to the environment should take place concurrently. The maximum distance from the tailings area at which water should be sampled will depend on the proximity of human settlement and exposure scenarios but will ultimately be dictated by experience.

Sampling frequency varies with site conditions but for the most part, monthly intervals before and during operations and quarterly intervals afterward have been recommended. Measurements related to operating tailings pond effluent should be made weekly.

9.4.3 GROUNDWATER

Monitoring of groundwater in the vicinity of a tailings disposal site is conducted because the subsurface movement of contaminated water represents a potential critical pathway. This is especially true where drinking water wells are in the immediate vicinity (5 km radius) of a site. Groundwater wells for drinking water are not common near the remote uranium mining sites on the Canadian Shield.

The layout of monitoring wells requires some knowledge of the hydraulic gradient at the tailings disposal site. This can be anticipated from topography and local subsurface geology and later confirmed by injection of tracers into upgradient boreholes. At least two monitoring wells upgradient and downgradient of the tailings basin are usually required.

Quarterly or semi-annual well sampling is adequate during the pre-operational and operational phases, and annual sampling during the transitional phase. For long-term purposes, one sample every three to five years is sufficient.

9.4.4 AIR

Air quality monitoring programs at tailings sites focus on two parameters: airborne particulate matter and radon. The following discussion describes monitoring considerations at tailings sites during and after decommissioning.

For the assessment of both airborne particulate matter and ambient radon concentrations in the vicinity of tailings areas, site-specific meteorological data must also be collected. The annual windspeed and direction frequencies, should logically be used to select sampling locations for both parameters. The remainder, i.e., barometric pressure, atmospheric stability, rainfall and temperature, must accompany each set of air quality sampling measurements.

9.4.4.1 Airborne Particulate Matter

A mixture of particles can become airborne at a tailings pile, given the proper surface conditions and adequate surface windspeed. A significant portion of these are chemically innocuous and occur in insufficient quantities to represent a hazard. The main concern, therefore, lies with particulate radionuclides, which constitute the prime source of inhaled radioactivity. Most particulate radionuclides are members of the U-238 decay series, but where natural thorium is present, members of the Th-232 decay series may also be present.

The location of sampling points is determined during the pre-operational phase and is based on windspeed and direction data. Points should surround the tailings pile and a significant number should be clustered roughly along the dominant annual or seasonal wind vector, at the downwind end of the tailings pile.

The total number of sampling points recommended depends upon:

- the physical stability of the tailings pile and its susceptibility to aeolian erosion,
- whether the pile has been or will be covered by a natural or synthetic liner,
- whether there is, or will be, a vegetative cover, and
- the susceptibility to erosion in terms of particle size distribution, moisture content and overall morphology.

The local topography and vegetative cover, in either their original condition or altered following reclamation activities, influence pile erosion susceptibility and consequently, the suitability of sampling locations. In general, wind erosion and suspension of particulate radionuclides in dust is not a major radiological pathway at Canadian tailings sites. However, dusting and surface erosion have occurred in the past at the Nordic and Stanrock tailings areas (Elliot Lake) (Environmental Assessment Board of Ontario 1979). Mitigative measures there have included water spraying, lime application, frost fencing and the development of vegetation covers.

The term "airborne particulate matter" encompasses a range of particle sizes which can be roughly classified into two groups: "dustfall" and "suspended particulate matter." The former refers to all settleable particulate material in the atmosphere whereas the latter generally denotes that fraction less than 44 μm in diameter. For the purposes of estimating doses of radiological constituents, the "respirable" particle size fraction, i.e. that comprising particles less than 10 μm, is of particular concern.

Sampling frequency and duration are subject to great variability. On the downwind side of a non-stabilized tailings pile, in the early autumn or spring when surface windspeeds are usually highest, a sufficiently large sample may be collected within only 6-8 hours. For most environmental sampling, it is often necessary to collect composite samples over several days to obtain a sufficient amount of suspended particulate for analysis.

By contrast, dustfall sampling involves the upright placement of an open jar of known dimensions at an open site for consecutive periods of 30 days. At the end of these periods, the collected material is analysed for the same constituents as are the airborne particulate samples (see below).

All airborne particulate matter collected should be analysed for natural uranium, Th-230, Ra-226 and Pb-210. Where the thorium content is greater than 30% of the uranium content, analyses should be extended to include Th-228, Th-232 and Ra-228. Heavy metal analyses are also recommended.

9.4.4.2 Radon

A monitoring program for radon gas consists of ambient air concentration sampling at the same locations as for the airborne particulate matter samples, and exhalation measurements taken upon the tailings themselves. The ambient concentrations of radon provide an indication of the magnitude of health risk to critical receptors due to exposure to radon daughters and, in the context of compliance monitoring, they are of most concern.

Ambient radon can be measured using devices which analyse grab samples virtually instantaneously or by passive monitoring methods which measure average ambient concentrations over periods of several weeks (Golder Associates and SENES Consultants 1985). The timing of sampling should coincide with that of radon flux sampling (see below). Data on the radon emanation coefficient may also be collected.

Radon exhalation data from bare tailings surfaces serve primarily to assess the need and type of remedial activity required to minimize this flux from the tailings in the long-term and to feed predictive models. They are also used to assess health risks for situations in which exposures may occur due to intrusion onto the tailings area by humans. Exhalation data from the pre-operational and operational phases of activity provide the basis for evaluating the effectiveness of the reclamation techniques applied during decommissioning. For example, if an earth cover is applied to a tailings surface, exhalation measurements made after application of the cover can be compared with those made before. The radon gas exhalation rate is usually measured by inverting a cylindrical container with one open end onto the tailings surface and measuring the increase in concentration of radon within it over time.

Once a tailings area becomes active, a network of exhalation sampling points should be established to provide data representative of most of the surface, though it is expected that tailings composition (and radioactivity) would be essentially homogeneous, giving rise to little spatial variation in radon flux. A total of ten points, distributed in an orthogonal grid or radial pattern, has been suggested, but this will vary with the tailings size and shape.

Among the factors controlling radon emanation, moisture content and temperature should be important considerations in monitoring program design. To assess the conditions under which maximum surface flux occurs, monitoring should be conducted during the summer months. Since atmospheric variables other than wind speed and direction (barometric pressure, stability) can also play important roles, a range of weather conditions should be included in the program. These considerations may warrant frequent monitoring where average surface flux is high. Elsewhere, especially where covers have been applied effectively, monitoring for more than one week each year may be superfluous.

9.4.5 MONITORING PROGRAM FOR A DECOMMISSIONED FACILITY

The Beaverlodge mine/mill was decommissioned and reclaimed during the period 1983 onwards. Essentially all work is complete. A transition monitoring program has been developed to assess the effects of the facility and demonstrate its performance, compared to modelling and engineering predictions. The plan is site-specific but demonstrates the type of data and level of effort required to monitor a reclaimed mining facility.

9.5 ASSESSMENT TECHNIQUES

9.5.1 PATHWAYS ANALYSIS

The possible effects that radioactivity released from a uranium tailings area might have on the public is assessed by undertaking a pathways analysis. Such an analysis is used to estimate the exposure or dose that certain critical groups (those most likely to receive the highest exposures) could receive by all of the possible pathways of exposure. Potential exposure pathways include drinking water, consuming fish from nearby waters, eating locally grown vegetables and inhaling air, all of which may contain radioactivity released from the facility. The results of these calculations can be compared with the appropriate standards or other points of reference such as natural variability in background radiation levels.

It is important to recognize that all such calculations are inherently uncertain; for example, the mathematical models (such as those that predict air dispersion of gaseous or suspended particulate matter), are at best only approximations. Moreover, the parameters used in the models are often poorly defined. In view of such uncertainties there is a tendency to incorporate conservative measures which lead to overestimates of exposure in pathways analysis. Care must be taken to avoid introducing so large a bias that the predicted dose indicates an inappropriate measure of risk (harm) from the proposed activity.

Radioactive materials released to the environment may result in exposure to man through various physical, chemical and biological processes. Such processes include the movement or transportation of radionuclides in the environment (usually via air or water), the uptake or bioaccumulation of radionuclides by local plants and animals, and the living conditions or lifestyle of the exposed individual (usually referred to as a receptor). The relative influences of these processes on predicted exposures vary from location to location and person to person.

Radiological exposures resulting from the development of a uranium mine/mill facility can be calculated through the use of mathematical models that simulate the behaviour of radionuclides in the environment. Figure 9.5-1 illustrates several of the potential pathways (routes that lead to exposure) that might be incorporated into a model. Various models have been developed for pathways analysis.

Models can be adapted to suit the situation being studied. Pathways that are not appropriate for a specific situation can be eliminated from an analysis. For instance, if the source term to the groundwater is known not to occur because seepage losses are very low the pathway related to this release need not be modelled. Conversely, extra effort can be directed to those pathways known or suspected of being particularly relevant to a specific situation. For example, when it is known that an individual of interest hunts locally for meat, this pathway can be added to the model and information gathered about hunting habits.

Model selection, modification, and application requires information about the type and nature of the source terms, the surrounding environment, and the location and lifestyle of the individuals most likely to be exposed.

Based on their information requirements, the models commonly used in radiological risk assessment for uranium mine/mill developments can be divided into four components: source characteristics, environmental distribution (dispersion and uptake), receptor considerations and dose calculations.

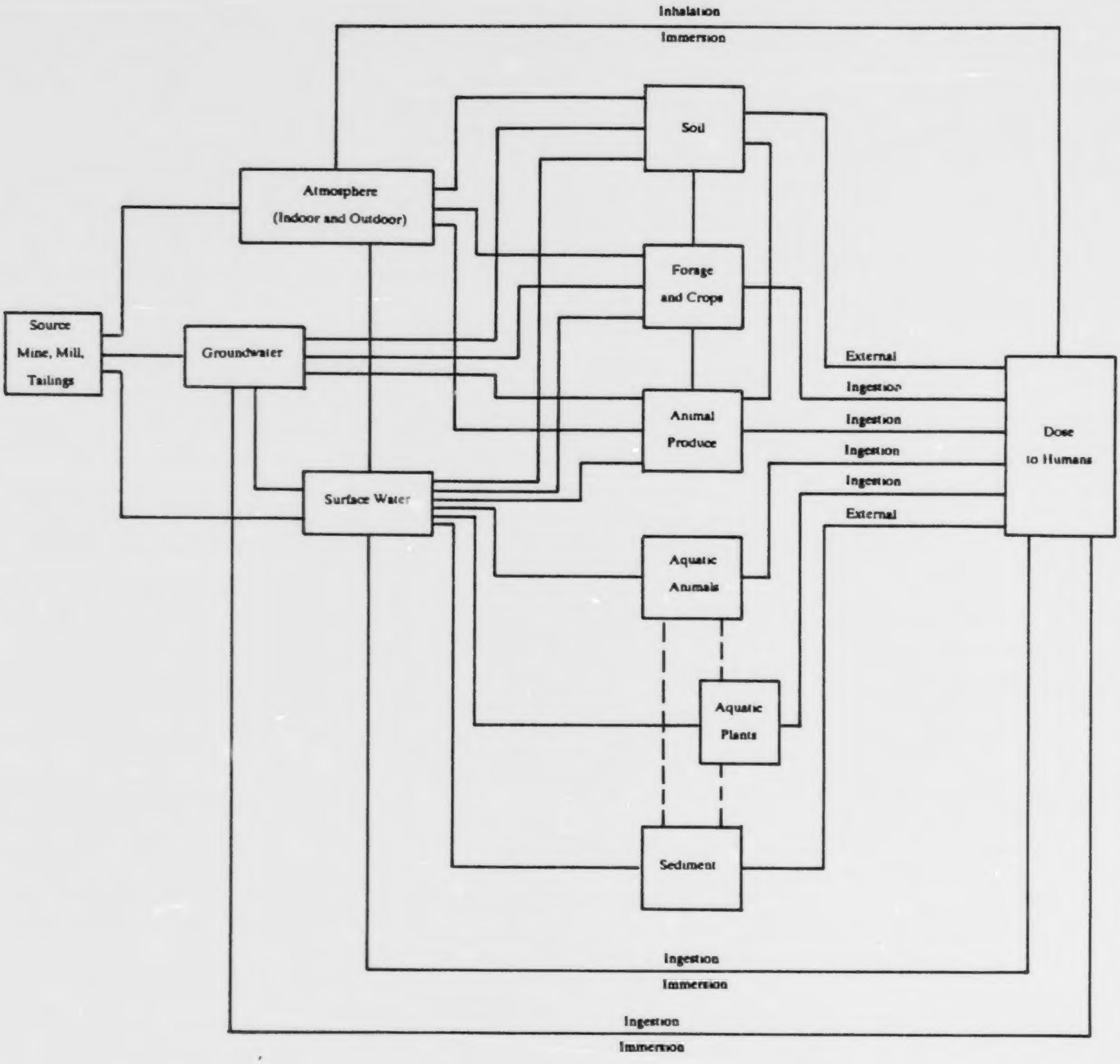
9.5.2 PROBABILISTIC AND RISK ANALYSIS

Probabilistic analysis is becoming an increasingly popular tool for assessing the environmental effects and risks associated with waste management. A probabilistic analysis employs the same mathematical models as the deterministic analysis. However, the approach explicitly accounts for uncertainty in the input parameters by considering a probability distribution, rather than a single value. The model is evaluated many times with new values selected for the input parameters. The parameters used in each trial are randomly selected from the appropriate distributions using a computerized random sampling technique. With this approach, many individual estimates of the "effect" are obtained by simply performing the number of trials desired. The results of such a probabilistic analysis are conveniently summarized by ordering the values into a frequency plot and calculating desired summary statistics (e.g. mean, standard deviation, percentiles, etc.). The concept of probabilistic analysis is illustrated in Figure 9.5-2. It has the advantage over the deterministic approach in that the full range of uncertainty in the parameter values may be incorporated into the analysis in an attempt to avoid the usual one-sided bias in the input specifications and results.

It is necessary to consider not only probability of failure but the consequences of failure. The concept of 'risk' and 'hazard' need to be considered. Risk may be defined as a compound measure of the probability and magnitude of adverse effects, or

Risk = Uncertainty x Damage

Other definitions of risk are 'the chance of encountering harm or loss' or the 'degree of probability of such loss' (Federal Emergency Management Agency 1984).


Inhalation
Immersion
Soil
Atmosphere
(Indoor and Outdoor)
Forage
and Crops
Source
Mine, Mill,
Tailings
Groundwater
External
Ingestion
Animal
Produce
Ingestion
Dose
to Humans
Ingestion
Surface Water
Ingestion
External
Aquatic
Animals
Aquatic
Plants
Sediment
Ingestion
Immersion
Ingestion
Immersion

Note:

1. Dotted lines indicate pathways that are not usually explicitly modelled, but are implicitly included in other modelling

Figure 9.5-1 Generalized Source, Environmental Transfer and Dose Model

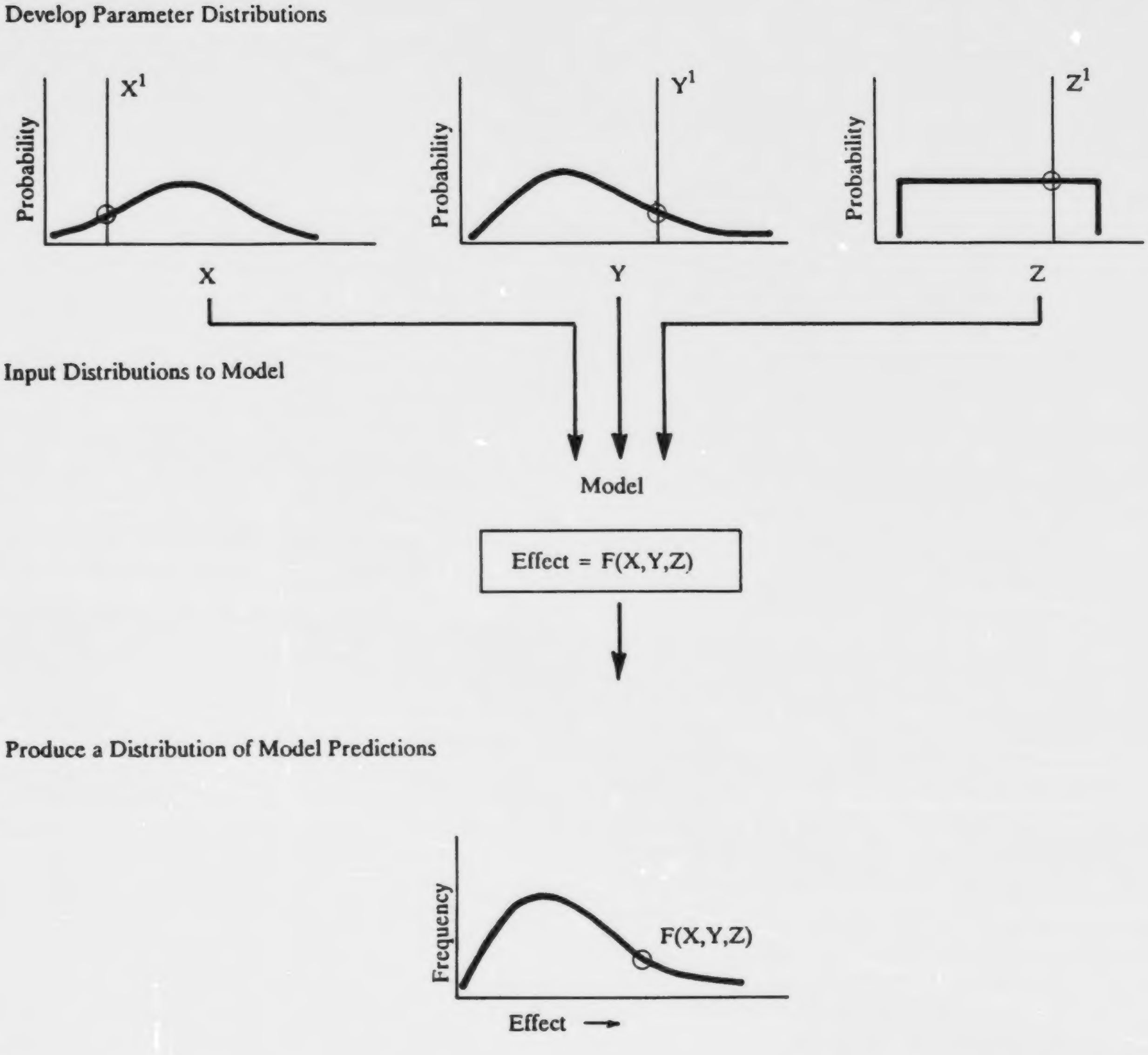

Develop Parameter Distributions
Probability
X^1
X
Probability
Y^1
Y
Probability
Z^1
Z
Input Distributions to Model
Model
Effect = F(X,Y,Z)
Produce a Distribution of Model Predictions
Frequency
F(X,Y,Z)
Effect →

Figure 9.5-2 Probabilistic Analysis

The dictionary defines hazard as a 'source of danger'. Hazard, therefore, simply exists as a source. Risk includes the likelihood of conversion of that source into actual delivery of loss, injury or some form of danger. Also,

Risk = Hazard/Safeguards

This implies that risk may be kept as small as desired by increasing the safeguards. As a matter of practical reality, however, risk can never be brought to zero (Federal Emergency Management Agency, 1984).

Various aspects of reliability analyses are discussed elsewhere (Harr 1984 and Whitman 1984). The major principles and procedures, as they relate to uranium tailings impoundments have also been considered (van Zyl and Robertson 1987).

As pointed out by The Royal Society (1983) the management of risks that are not unacceptable must include consideration of the cost of control, and acceptable levels of risk. They judged for example that the acceptable level of annual risk of death to the individual was somewhere between 10^{-3} and 10^{-7}. They conclude that:

> It is principally in between these upper and lower levels that risk management should consist of comparing risks, detriments, costs and benefits.
>
> Above the upper level, the risks must be reduced or the operations suspended, whatever the cost. Below the lower one even the effort needed to make the comparisons cannot be rationally justified.
>
> These figures apply to risks to the individual - in practice to the individuals most highly at risk in a particular situation because the exposure to risk is never uniformly distributed across the exposed group. Catastrophic accidents, killing or injuring many people as the result of one event, have little influence on the level of individual risk but have a disproportionate effect on the response of society. There is a clear desire to ensure that large accidents have a more than is proportionately lower probability than small ones but firm relationships between size and probability have yet to emerge as indicators either of unacceptability or of trivality.

This is clearly the case with regard to the nuclear industry and uranium mining, milling and waste disposal, despite ALARA concepts. As pointed out by Slovics et al 1980, the perceptions that radioactive hazards provoke are different from those elicited by other types of risk.

Recently the risk assessment and management of uranium mill tailings has been the subject of a report by the U.S. National Research Council, Commission on Physical Sciences, Mathematics and Resources (NRC 1986). They assembled a multidisciplinary panel of scientists, engineers, chemical and health experts, and dealt with the following issues:

- exposure processes,
- potential biological hazards,
- technical alternatives for tailings management, and
- problems of the assessment and management.

A list of specific conclusions and recommendations was made on each of these issues. Although large-scale serious health risks are not envisaged, the panel favoured "adaptive look-ahead" risk-management strategy, believing it to be more consistent with present scientific understanding of the problem, rather than an approach based on a "one-time" fix. They suggested that assured pile integrity over a period of a thousand years without periodic inspection and maintenance, is a "scientifically unrealistic goal". Clearly this slaps in the face of conventional wisdom on walkaway disposal strategy.

9.5.3 THE UTAP MODEL

The Uranium Tailings Assessment Program (UTAP) was developed on behalf of the NUTP to analyse the long-term effects of uranium mill tailings. The UTAP model is a probabilistic model and is described in detail, (SENES 1987).

UTAP was developed in a modular fashion, and consists of a number of "control" and "component" modules. Component modules are the computer implementation of the mathematical models used to describe the tailings and surrounding environment. Control modules provide the infrastructure required for probabilistic analysis. The modular approach facilitated program development and quality assurance and will allow UTAP to be easily modified in the future for application to specific sites.

UTAP models the behaviour of four radionuclides (natural uranium, total thorium, radium-226 and lead-210) and a number of inorganic chemical species as well as pH. Seven different exposure pathways are modelled, including:

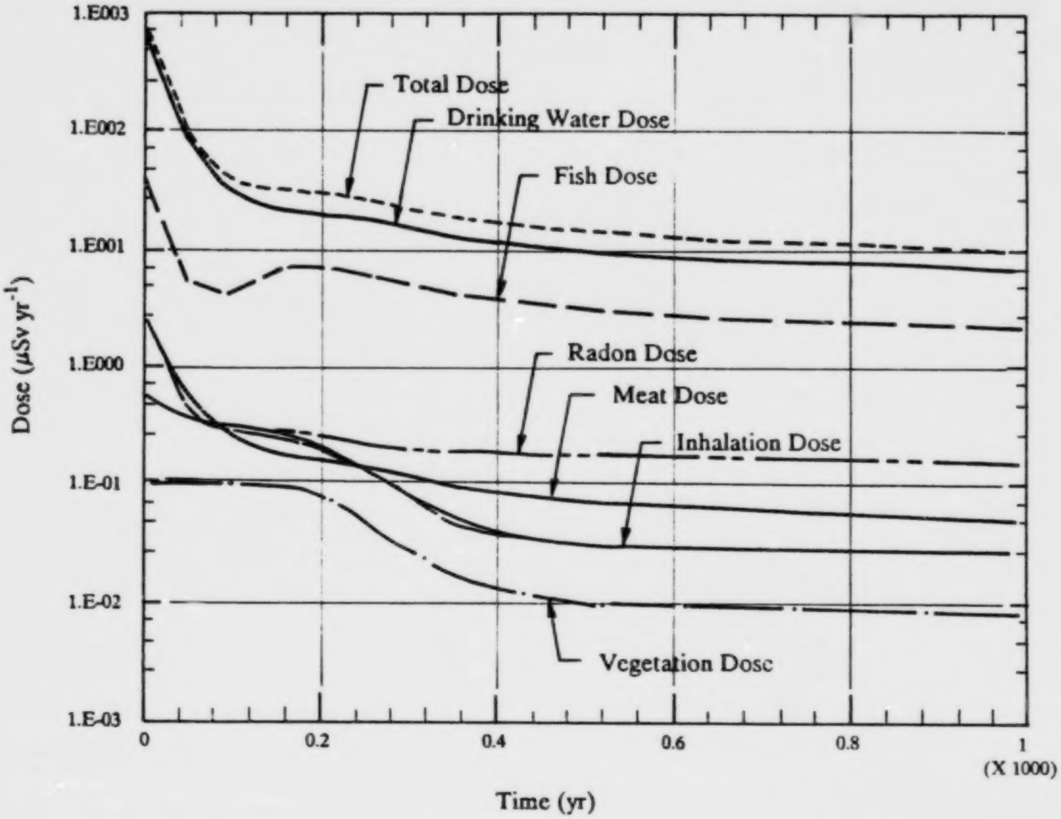
- radon inhalation,
- dust inhalation,
- external exposure (groundshine),
- ingestion of vegetables,
- ingestion of meat (caribou, moose and deer),
- ingestion of water, and
- ingestion of fish.

UTAP requires considerable information as user-specified input to the program. This provides much greater flexibility than having the same information "built-in" to the computer program. Some noteworthy UTAP features include the capabilities to:

- perform calculations in all directions, for up to 50 km from the tailings site,
- incorporate an entire watershed, with user-specified characteristics,
- model receptors of two types, at up to 80 different locations,
- perform calculations for up to 1000 years, in time steps of 1 or 10 years,
- model two distinctly different tailings disposal scenarios, and
- simulate further disposal scenarios by modifying input parameter distributions and/or component modules.

These capabilities allow one to generate and access a large amount of information. The assimilation, analysis and interpretation of this quantity of information can become a very complex task. It is substantively simplified in UTAP by the computation of recursive ("on the fly") summary statistics. However, access to commercially available data management software is required to enhance data manipulation and reduction.

The results generated by UTAP for the hypothetical Elliot Lake type tailings facility indicate that water-related pathways contribute the greatest dose to those receptors on the affected watershed. These primary exposure pathways involve direct consumption of water and fish. The geometric mean for dose from an Elliot Lake generic facility as described (SENES 1986c) is provided in Figure 9.5-3. For this scenario, it was assumed that the dams were stable and that no reclamation was undertaken when the basin was abandoned.



Note: Geometric mean values of 200 trials

Figure 9.5-3 Dose vs. Time by Pathway

It is noteworthy that under these conditions, the long-term dose to the selected critical receptor is very low (i.e. <0.1 m Sv/a after 40 years).

9.5.4 ALARA ANALYSIS

The ICRP provides guidance to many countries on matters of radiation protection, the safe use of radiation, and the development of radiological protection regulations. The system of dose limitation recommended by the ICRP is enunciated in Publication 26 (ICRP 1977) and based upon the following three principles:

(a) no practice shall be adopted unless its introduction produces a positive net benefit;

(b) all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and

(c) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

The first principle is commonly referred to as the "justification" principle. The second principle is often cited as the "optimization" principle and is commonly referred to as "ALARA" (an acronym for as low as reasonably achievable, social and economic factors taken into account). The third principle calls for individual dose limits.

The ALARA principle has become a major objective of the practical application of radiological protection programs in many countries including the United States (at least in the sense of cost-benefit analysis). The ALARA concept recognizes the generally accepted assumption that there may be no dose, no matter how small, that does not entail some increased risk. Since a totally risk-free threshold dose cannot be identified, the optimization process represents a technique for determining an appropriate control level below the maximum individual dose limits.

At the heart of risk-benefit (or cost-benefit) analysis is the comparison of the risks (or costs) and benefits of a particular project, program, or event to determine if a net benefit will ensue. Indication of a net benefit can be used to support a decision to proceed while a net cost suggests that an alternative approach should be considered.

Concepts such as ALARA are directed not just to determining whether a net benefit or net cost will occur, but to extending beneficial actions until the point is reached where the next incremental increase of benefit is balanced by an equal increase in cost.

CHAPTER 10.0
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SYMBOLS

&

GLOSSARY

SYMBOLS

Bq	- SI unit of activity, the becquerel
c	- cohesion of the material
C_c	- compression index
C_i	- Curie unit
C_v	- coefficient of consolidation
d	- dispersivity
D	- total depth of flow
D_r	- relative density
D_{10},D_{15},D_{60}	- the diameter of the 10% passing size of the material, and the 15% passing size the 60% passing size of the material respectively
e	- the void ratio of the soil as it exists in situ
e_{max}	- the void ratio of the soil in its loosest state
e_{min}	- the void ratio of the soil in its densest state
h	- height of the waste embankment or pile, and the difference in piezometric head between the point of seepage entry and the point of seepage exit
i	- hydraulic gradient along flow path
I_p	- plasticity index
k	- permeability
k	- coefficient of permeability
L	- Litre
L_w	- liquid limit
n	- porosity
Q	- quantity of flow
R	- retardation factor
σ	- total normal stress
S_v	- man-sievert unit for radon irradiation

q - flow of water, and rate of seepage per unit length perpendicular to the plane of the flow net

S - shear strength

S_r - degree of saturation

t_s - the soil surface temperature

u - pore water pressure on the failure plane

U - coefficient of uniformity, and the thermal diffusivity

v - Darcy's velocity

β - slope angle

γ - unit weight in saturated state

γ_d - unit weight in dry state

γ_s - unit weight of the soil particles

γ_w - unit weight of water

ϕ - angle of internal friction

ϕ' - effective angle of internal friction

GLOSSARY

ABLATION. The combined processes by which a glacier wastes.

ACTIVITY. The activity of a quantity of a radioactive material is the number of spontaneous nuclear transformations which occur in this quantity per unit time. The SI unit of activity is the becquerel (Bq), which has superseded the curie (Ci).

ANGLE OF INTERNAL FRICTION, ϕ. The maximum angle between the normal and the resultant stress acting on a surface of contact within a soil or rock.

ARCHEAN. Oldest rocks of the Precambrian.

AXIS OF DAM. The plane or curved surface, arbitrarily chosen by a designer, appearing as a line, in plan or in cross section, to which the horizontal dimensions of the dam can be referred. Usually parallel to the crest of the dam.

BARRIER (NATURAL OR ENGINEERED). A feature which deals or prevents radionuclide migration from the waste and or repository into its surroundings. An engineered barrier is a feature made by or altered by man.

BENTHIC. Flora & fauna of bottom of lake.

BERM. A horizontal step in the sloping face of an embankment dam.

BORROW MATERIAL. Soil material excavated from the foundations of a tailings impoundment or specially designated borrow pit, and used in embankment or tailings dam construction.

BUFFER ZONE. A designated controlled area surrounding a tailings disposal site to ensure an adequate distance between the installation and places used by, or accessible to, the public.

CAPILLARITY. The rise of fluid in the pore spaces in a soil or tailings deposit. It is caused by surface tension.

COEFFICIENT OF CONSOLIDATION, C_v. A coefficient indicating the rate of compression in soil under load.

COEFFICIENT OF PERMEABILITY, k. The rate of discharge of water under laminar flow condition through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and at standard temperature (20°C).

COEFFICIENT OF UNIFORMITY, U. The ratio of the 60% passing size of the material to the 10% passing size of the material, $U = D_{60}/D_{10}$.

COFFERDAM. A temporary structure enclosing all or part of the construction area so that construction can proceed in the dry. A diversion cofferdam diverts a river into a pipe, channel or tunnel.

COHESION, C. The portion of the shear strength (s) indicated by the term c in the equation: $s = c + \sigma \tan \phi'$, where ϕ' is the angle of internal friction. It has the nature of an intergranular binding force.

COLLECTIVE DOSE EQUIVALENT. The collective dose equivalent to a population, expressed in units of man-sievert (man Sv) or man-rem, that, i.e., the sum of the products of the individual or per capita dose equivalents and the number of individuals in each exposed group in a population.

COMPRESSIBILITY. Change of specific volume & density under hydrostatic pressure.

COMPRESSION INDEX, C_c. An index indicating the compressibility of the soil, representing the slope of the curve of void ratio versus logarithm of effective pressure.

CONDUITS. Any channel, pipe, etc., for flowing water.

CONFINEMENT (OR ISOLATION) OF WASTE. The segregation of radionuclides from the human environment, and the restriction of their release into the environment in unacceptable quantities or concentrations.

CONSOLIDATION. The process of transient flow of water through a soil structure which compresses or expands in time is called consolidation in soil mechanics.

CONTACT GROUTING (BLANKET GROUTING). Filling, with cement grout, any voids existing at the contact of two zones of different materials, e.g., between a dam foundation and the underlying rock.

CORE, IMPERVIOUS CORE, OR IMPERVIOUS ZONE. A zone of material of low permeability in an embankment dam.

CREST LENGTH. The developed length of the top of the dam including the length of spillway.

CREST OF DAM. The upper part of an uncontrolled spillway. The term "Crest of Dam" should not be used when "Top of Dam" is intended.

CREST. The top of an embankment dam or dyke.

CRITICAL SURFACE (CRITICAL FAILURE SURFACE). The sliding surface for which the factor of safety is a minimum in an analysis of a soil sliding in an embankment.

CUTOFF TRENCH. The excavation later to be filled with impervious material so as to form the cutoff. Sometimes, used incorrectly to describe the cutoff itself.

CUTOFF. An impervious construction by means of which water is prevented form passing through foundation material.

DECANT PIPE. Pipes buried in tailings embankments for the purpose of water drainage.

DECANT SOLUTION. Solution which is removed from the surface of a waste retention system after the solids have settled out.

DEGRADATION. Lowering of land surface by erosive processes, especially by the removal of material through erosion and transportation by flowing water.

DEGREE OF SATURATION, S. The ratio of the volume of water in the soil voids to the total volume of voids.

DENSITY (MASS DENSITY). Mass per unit volume. Relative density - the density relative to its maximum and minimum values.

DESICCATION. The removal of moisture by drying from the surface of a soil or tailings deposit.

DESIGN LIFE. The period of time during which the tailings impoundment is designed to perform with respect to the rates of release of radionuclides and the retention of tailings material.

DIAPHRAGM. See MEMBRANE.

DIKE, (DYKE). A long, low embankment. The height is usually less than four to five meters and the length more than ten or fifteen times the maximum height.

DISPOSAL. The emplacement of waste materials in a repository without the intention of retrieval.

DIVERSION CHANNEL OR CHANAL. A waterway used to divert water from its natural course. The term is applied to a permanent or temporary arrangement, e.g., to bypass water around a dam during construction.

DOSE COMMITMENT. The integral over infinite time of the average dose rate to a specified population.

DOSE EQUIVALENT. The product of absorbed dose and quality factor and other modifying factors necessary to obtain an evaluation of the effects of irradiation received by exposed persons, so that the different characteristics of the exposure are taken into account. It is commonly expressed in units of sieverts (Sv) or rems.

DRAINAGE BLANKET. A drainage layer placed directly over the foundation material.

DRAINAGE LAYER. A layer of pervious material in an earthfill dam to relieve pore pressures or to facilitate drainage of the fill.

DRAINAGE WELL OR RELIEF WELL. Vertical wells or boreholes downstream of, or in downstream shoulder of, an dam to collect and control seepage through or under the dam and so reduce water pressure. A line of such wells forms a drainage curtain.

DRUMLIN. Elongated hills of gravel, or sometimes till generally parallel to the direction of glacier movement.

EFFECTIVE STRESS. The average normal force per unit area transmitted from grain to grain in a granular mass. It is the stress that is effective in mobilizing internal friction, and equals the total stress less the pore water pressure.

EFFLUENT. A liquid or gas which flows out of a containing space into the environment.

EMANATION. Radioactive gas formed by decay of a radioactive solid.

EMBANKMENT (OR TAILING DAM). A raised earthen structure designed to retain liquid and solid wastes. The embankment may be built using tailings, other materials, or a combination of both.

EXCAVATION. The space created by the removal of soil or rock for the purpose of construction.

EXHALATION. Escape of gases form a radioactive solid into the atmosphere.

FACE. With reference to a structure, the external surface which limits the structure, e.g., face of a dam.

FACTOR OF SAFETY. The ratio of available shear strength to shear stress on the critical failure surface.

FILL. Man-made deposits of natural earth materials (soil, rock) and/or waste materials.

FILTER OR FILTER ZONE (GEOTECHNICAL). A band of granular material which is incorporated in an embankment dam and is graded (either naturally or by selection) so as to allow seepage to flow across or down the filter zone without causing the migration of the material from zones adjacent to the filter.

FILTRATION (MINE PROCESSING). Methods of reworking water from tailings at the mill prior to disposal in the tailing impoundment.

FINGER DRAINS. A series of parallel drains of narrow width (instead of a continuous drainage blanket) draining to the downstream toe of the embankment dam.

FISSURE. Extensive crack, break or fracture in the rocks.

FLASHBOARDS. Length of timber, concrete or steel, placed on the crest of a spillway to raise the water level, but which may be quickly removed at time of flood.

FLOW LINE. The path that a water follows under laminar flow conditions.

FOUNDATION OF DAM. The natural soil or rock material on which a dam is placed.

FREEBOARD. The height measured from water level to the crest of embankment. The minimum freeboard should be measured from the maximum projected flood level to the crest of the embankment.

FROST ACTION. The phenomenon occurring when water and soil are subjected to freezing, which, because of the water-ice phase change or ice-lens growth, results in a total volume increase, and/or the build-up of expansive forces under confined conditions, and the subsequent thawing that leads to loss of soil strength and increased compressibility.

FROST-SUSCEPTIBLE SOIL. Soil in which significant ice-segregation will occur, resulting in frost heave, or heaving pressures, when requisite moisture and freezing conditions exist.

FROUDE NUMBERS. In model analysis, the ratio should be the same in the model and full-size project.

GABION DAM. Special name given to a crib dam when built up of gabions.

GEOMORPHIC. Pertaining to the form of the earth's surface.

GEOTECTONIC. Pertaining to the form, arrangement and structure of the rock masses composing the earth's crust.

GNEISS. Having composite structure of alternating schistose and granulose bands and lenses which differ in mineral composition and texture.

GROUT CUTOFF (GROUT CURTAIN). A vertical zone, usually thin, in the foundation into which grout is injected to reduce seepage under a dam.

GROUND WATER LEVEL. The level below which the pores spaces, fissures and joints of the rock and subsoil, down to indefinite depth are full of water.

GROUNDWATER. Water which permeates geological strata, filling their pore spaces, fissures and joints.

HYDRAULIC GRADIENT. The loss per unit distance of elevation head plus pressure head.

HYDROCYCLING. A procedure used for dam and embankment construction in which hydrocyclones or cyclones can be used to separate sands from the slimes. A series of cyclones can be placed along the crest of the embankment or a group of cyclones can be mounted in parallel as a mobile unit which travels along the crest of the dam.

HYDROSTATIC PORE-WATER PRESSURE. Water pressure varying directly in a free-standing column of water.

ICE-SEGREGATION. The growth of ice in lenses, layers, and veins in soil, commonly (but not always) oriented normal to the direction of heat loss.

INTERNAL EROSION. The formation of voids within soil or soft rock caused by the mechanical or chemical removal of material by seepage.

JAROSITE. Composition $KFe^3(SO_4)_2(OH)^6$, Yellow ochre to dark brown colour with vitreous lustre. Occurs in association with decomposing pyrite. Found around volcanic vents.

LEACHABILITY. The susceptability of a solid material to the removal of its soluble constituents by the dissolving or erosive action of water or other fluids.

LICENSE. Formal document, issued by a regulatory body for major stages in the development of a tailings impoundment facility, defined by regulations permitting the holder to perform specified activities.

LINING. A layer of material, clay, plastic, asphalt, etc., placed beneath a dam or tailing impoundment to provide watertightens or to prevent erosion.

LIQUEFACTION. A transformation in which the soil particles become temporarily suspended in the pore water and the soil mass suddenly flows.

LIQUID LIMIT, W_L. The water content at which the soil exhibits a small shearing strength is taken to be the boundary between liquid and plastic behaviour and this water content is called the liquid limit. It is measured in the Atterberg apparatus.

LONG-TERM. Periods of time that exceed the time during which administrative controls can be expected to last. In this manual it is the period of time exceeding the design life of a tailings impoundment facility.

MORPHOLOGY. Study of the forms of the land's surface.

OVERTOPPING. Water overflowing the crest of the tailings embankment, dam or dyke.

PEAT. A highly organic soil consisting chiefly of decayed remains of vegetable matter.

PERCHED GROUNDWATER TABLE. A body of water in the ground above the groundwater level.

PERMEABILITY. The permeability of soil or rock is its capacity for transmitting water, measured by the rate at which water can move a given distance in a given period of time, and is expressed m/s.

pH. The negative logarithm of the hydrogen ion activity, indicating acidity (low values) or alkalinity (high values).

PHREATIC. Pertaining to all water in the zone of saturation.

PIEZOMETER. A device for measuring the hydrostatic pressure at a point in the ground. Simple piezometers are open holes for measuring the groundwater table.

PINGOS. Large mound raised by frost action above the permafrost and generally persisting for more than a single season.

PIPE DRAINS. A drainage system which consists of pipes in the embankment or dyke.

PIPING. The progressive development of internal erosion by seepage, through the embankment or foundation appearing downstream as a hole discharging water.

PITCHBLENDE. Massive or amorphous uraninite.

PLASTIC LIMIT, W_p. The water content representing a change of the soil from a plastic to a brittle material.

PORE PRESSURE. The interstitial pressure of fluid (air or water) within a mass of soil, rock, or concrete.

PORE WATER PRESSURE, u. Stress transmitted through the pore water.

POROSITY. The ratio of the volume of the pore spaces in a rock or soil to its total volume.

PRESCRIBED LIMITS. Limits established or accepted by the regulatory body.

RADIATION PROTECTION OR RADIOLOGICAL PROTECTION. All measures associated with the limitation of the harmful effects of ionizing radiation on people, such as limitation of external exposure to such radiation, and of bodily incorporation f radionuclides, and prophylactic limitation of bodily injury resulting from either of these. All measures designed to limit radiation-include damage in materials.

RADIOACTIVE MATERIAL. A material in which one or more of its constituents exhibit radioactivity. For regulation purposes, this term may be restricted to radioactive material with a radioactivity level of specific activity greater than a specified value.

RADIOACTIVE WASTE. Any waste material that contains or is contaminated with radionuclides at concentrations or radioactivity levels greater than limits established by the regulatory authority.

RADIOACTIVITY. The property of certain nuclides of spontaneously emitting particles or gamma or X-radiation following orital electron capture, or of undergoing spontaneous fission.

RADIONUCLIDE MIGRATION. The movement of radionuclides through various media due to fluid flow and or by diffusion.

REGULATORY AUTHORITY OR REGULATORY BODY. A designated national authority or system of authorities as having eh legal authority for conducing the licensing process, for issuing of licenses and for regulating the siting, design, construction, commissioning, operation, shot-down, decommission and subsequent control of nuclear facilities (e.g., a tailings disposal site) or specific aspects therefore.

REHABILITATION. Actions taken further than stabilization of tailings impoundments to allow for other uses of the area, or to restore the area to near-pristine conditions.

RIGHT ABUTMENT. The abutment on the right-hand side of an observer when looking downstream.

RIPRAP. A layer of large uncoursed stones, broken rock or precast blocks paced in random fashion on the upstream slope of an embankment dam or on the sides of a channel as a protection against wave and ice action. Very large riprap is sometimes referred to as "armoring".

ROASTING. Hot Air metallurgical process to drive off arsenic.

SADDLE DAM. A subsidiary dam of any type constructed across a saddle or low point on the perimeter of a tailings pond.

SATURATED. All the interstices are filled with water.

SEEPAGE. The interstitial movement of water that may take place through a dam, its foundation, or abutments.

SEISMIC EVENT. An earthquake.

SHEAR STRENGTH. The internal resistance offered to shear stress. It is measured by the maximum shear stress, based on original area of cross section, that can be sustained without failure.

SHOULDER (SHELL). The upstream and downstream parts of the cross section of an dam on each side of the core or core wall. Hence the expression upstream shoulder or downstream shoulder.

SHUT-DOWN AND SEALING. Action taken, after disposal operations have ceased, to prepare an installation for abandonment or minimum surveillance.

SITE. The area containing a tailings disposal site that is defined by a boundary and that is under effective control of the licence holder.

SITING (OR SITE SELECTION). The process of selecting a suitable site for a tailing facility, including appropriate assessment and definition of the related basis of design.

SLOPE PROTECTION. The protection of embankment slope against wave action or erosion.

SLOPE. (a) Side of a hill or a mountain, or the incline face of a channal, or embankment, or the inclination from the horizontal, measured as to the ratio of the number of units of the vertical distance to the number of units of the horizontal distance. Expressed in percent when the slope is gentle; in this case also termed "gradient".

SLURRY TRENCH. A narrow excavation whose sides are supported by a bentonite mud slurry filling the excavation. Sometimes used incorrectly to describe the cutoff itself.

SOLIFLUCTION. Barely perceptible flow of saturated ground mass.

SPECIFIC GRAVITY. The ratio of the weight in air of a given volume of soil particles to the weight in air of an equal volume of distilled water at a temperature of 4°C.

SPIGOTTING. A procedure generally used in construction for dams or tailings embankments for which spigots are employed, the tailings slurry being discharged from a series of spigots along the crest of the dam or embankment. The slurry meanders in a series of streams that result in discontinuous horizontal stratification.

SPILLWAY. A structure over or through which floodflows are discharged.

STABILIZATION. Actions taken to prevent or retard movement of tailings material away from an impoundment due to the action of natural forces, such as gravity, wind or water erosion, and in a manner such that little or no surveillance and maintenance is required.

STOICHIOMETRY. Determination of equivalent weights of substances in chemical reactions.

STORAGE. The emplacement of waste in a facility with the intent that it will be retrieved at a later time.

STRESS. The force per unit area acting within a body.

SUMP. A pit in which water collects before being pumped out.

SURCHARGE FILL. A temporary thickness of fill placed on top of soil or tailing to promote consolidation and settlement. Usually left in place for 3 to 6 months.

TAILINGS. The residues resulting from grinding and otherwise processing the ore in a mill to extract the metal values.

TAILINGS IMPOUNDMENT. A structure above or below grade in which the tailings and tailings solutions are deposited, including all its elements such as embankment dams pit walls, liners, cove layers.

TAILINGS PILE. A deposit of tailings material.

TAILINGS SEEPAGE (OR LEACHATE). Seepage of liquid from a tailings retention system.

TAILINGS SOLUTION. Liquid associated with the tailings as they are deposited in the tailings impoundment.

TILL (GLACIAL TILL). Nonsorted, nonstratified soil deposited by a glacier.

THIOBACILLUS FERROOXIDANS. Sulphur oxidizing bacteria which accelerates the formation of acid mine drainage at low pH.

TOE OF DAM. The junction of the downstream face of a dam with the ground surface.

UNIT WEIGHT. Weight of soil or rock per unit volume.

UPSTREAM BLANKET. An impervious blanket placed on the floor of the pond upstream of a dam. In the case of an embankment dam, the blanket may be connected to the impermeable element.

VOID RATIO, E. The rate of the volume of the pore spaces to the volume of solids in a soil or rock.

VOLUME OF DAM. The total space occupied by the materials forming the dam structure computed between abutments and from top to bottom of dam.

WASTE EMBANKMENTS. All mine waste materials placed on surface but excludes those materials placed underground as backfill.

WASTE MANAGEMENT. All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste.

WASTE PILES. All waste embankments other than tailings or ore, resulting from a mining operation.

WASTE RETENTION SYSTEM. Storage system for liquid and solid wastes. This includes systems for wastes generated by the uranium mining and milling process.

WATER TABLE (OR PHREATIC SURFACE). The surface of the groundwater; the upper surface of a zone of saturation. Also defined as the surface on which the pressure in the water is equal to atmospheric pressure.

APPENDIX A

PIT SLOPE MANUAL (CANMET 1977)
CHAPTER 9 - WASTE EMBANKMENTS
SUMMARY

SUMMARY

GENERAL

The term "waste embankments" includes tailings dams, rock dumps and overburden or soil dumps. The design specifications in the manual deal primarily with stability with some consideration given to the effects on natural water courses and groundwater. Reclamation aspects are dealt with in the chapter on Environmental Planning.

Design for stability must take into account the strength of potentially weak foundations, the maximum slope angle that will be stable in the long-term even after the mine has shut down, and adequate natural drainage to prevent destabilizing water effects. Provisions for drainage must be explicitly designed as otherwise seeping water could cause softening of the embankment and internal erosion leading to breaching. For tailings dams, the requirements for water retention must also be considered. These include the appropriate amount of freeboard and crest width. For coal wastes, spontaneous combustion is another form of instability that must be prevented.

SITE INVESTIGATIONS

The site of a waste embankment will require some of the following ingredients of an investigation program:

- engineering and geological surveys,
- foundation testing,
- borrow pit testing,
- waste material testing, and
- topographic mapping.

Besides the mechanical properties needed for stability analyses, other properties will be of interest. Sedimentation properties of tailings will influence the retention time and depth of water required in the tailings ponds. The oxidation potential, particularly of sulphide minerals, is important when considering the possible effects of seepage on natural water courses. The ease with which coal in waste will combust spontaneously can be tested so that the need for special design requirements can be determined. The nature of the processing reagent expelled with the tailings effluents is also important in determining potential effects on natural water courses.

Climatic and ecologic data are required for tailings dams and revegetation planning. Air temperature, precipitation, wind, solar radiation and evaporation, measured at various stations across the country, are published by the Atmospheric Environment Service of the Department of Environment, Ottawa. Maps are available showing contours of temperature, humidity, wind, rainfall and snowfall. Records of measured streamflows are published by the Water Survey of Canada, Department of Environment.

Subsurface investigations are directed toward determining the nature of soil deposits overlying the bedrock. The thickness and composition of each strata are required. Information on groundwater regime and its variation over the years are desirable. Details of any old, current or future underground mine workings are important. Similarity, it is valuable to know of any solution caverns.

DESIGN

Rotational sliding is the typical mode of instability for water embankments. The cause might be slopes that are too steep for the type of material. Alternatively, it could result from overloading a weak foundation as the embankment is built up. The rise in water level in the embankment is often the triggering mechanism for instability.

Skidding on a sloping foundation sometimes occurs when the foundation is composed of weak clay or silt or has a thin layer of altered material on top of bedrock.

The appropriate analysis techniques to evaluate stability are described in detail in the design chapter. Except for foundation problems, embankment design has the advantage that the nature of construction material and the construction procedure are known to the engineer. Stability calculations, therefore, have more certainty than do analyses for mine slopes.

Liquefaction occurs when tailings in an embankment or pond become temporarily suspended in water and flow like a viscous liquid. When tailings dams are breached, liquefaction of the saturated slimes often occurs. In the embankment itself, if the tailings are in a lose state and saturated, vibration from earthquakes or trucks might cause liquefaction. Design must anticipate this, and if necessary, specify the deposition procedures or sequence or require drainage to avoid it.

Overtopping of a tailings dam can lead to breaching and loss of control of the tailings pond; this is probably the most common cause of dam instability. Design requires determining the appropriate freeboard and width of crest. Using construction material that is less subject to erosion than normal tailings may be necessary.

Erosion of embankment slopes can lead to instability. In tailings dams, the concentration of water flow at reentrant corners and other changes of contour, if not controlled, can lead to piping and ultimately to breaching of the dam.

Piping is the transporting of slide particles in seepage water passing through or under the dam. When sufficient material has been carried out by the water, a pipe may be formed extending progressively under the embankment until an excessive flow of water occurs, causing breaching of the dam.

Differential settling beneath an embankment may lead to fracturing of nearby pipes. Settling in tailings dams may crack the impervious seal which must be anticipated in the design.

Coal waste piles can be ignited by spontaneous combustion. Poisonous gases can be generated and the dump become very difficult to handle. In attempting to extinguish such a fire, the generation of coal dust could lead to an explosion. Design and construction of such dumps should take this hazard into account.

Seepage through tailings embankments should be inhibited and drawn into drains where it can be controlled. In this way, stability of the slopes is maintained and any environmental impact can be controlled.

The catchment area behind a tailings dam can be quite extensive. Consequently, relocation of streams, ditches and dikes should be considered as means to isolate the tailings pond from the adjacent catchment area. The storm flood that must be designed for is considerably reduced in this way, and the quantity of seepage effluent that might have to be treated is minimized.

CONSTRUCTION AND OPERATION

Tailings dams are commonly constructed by one of three methods - downstream, upstream, or fixed centreline. Stripping of organic matter and the cutting off of seepage contribute greatly to stability of the embankment.

A maintenance program is important after an embankment has been constructed, particularly for tailings dams. The conditions under which they exist change continuously. Problems can develop very quickly under intense operating conditions, particularly in the season of high precipitation. If severe erosion is anticipated, riprap or vegetation should be used to counter the problem.

The monitoring of crest movement and groundwater, particularly in tailings dams, gives early warning of unsatisfactory conditions developing. Such measurements should be an integral part of the mine monitoring program.

PERMAFROST

Placing waste embankments on permafrost can produce results that are not experienced in other areas. The permafrost line may rise into the embankment and result in slope instability if ice lenses are created that thaw in the summer. On the other hand, the permafrost line may recede further into the foundation, depending on the thermal regime, which could give rise to excessive settling if the thawed material is clay or silt. Embankments placed on permafrost slopes can be subjected to special conditions for sliding, groundwater flow and ice formation. Correcting these problems can be very difficult so that it is better to anticipate the difficulties and take appropriate measures to avoid them.

STEFFEN ROBERTSON & KIRSTEN

Geotechnical, Mining & Environmental Engineers

SUPPLEMENTARY REPORT
ON

FROST ACTION IN URANIUM TAILINGS

CANADIAN URANIUM MILL WASTE DISPOSAL TECHNOLOGY

Prepared for:

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ENERGY, MINES AND RESOURCES CANADA

Canada Centre for Mineral and Energy Technology
555 Booth Street
Ottawa, Ontario K1A 0G1

Prepared by:

STEFFEN ROBERTSON AND KIRSTEN (B.C.) INC.
#801 - 1030 West Georgia Street
Vancouver, B.C. V6E 2Y3

in Association with

CLIFTON ASSOCIATES LTD.
EBA ENGINEERING CONSULTANTS LTD.

Authors: A. MacG. Robertson
D.D. Kent
D.R. Williams
N.A. Skermer

MICROMEDIA

126 pp

SUMMARY

Canadian uranium tailings impoundments, specifically those in Saskatchewan, are located in climatic zones that have severe cold winter climates resulting in seasonal freezing or permafrost effects in the tailings. Frost effects may be disruptive to tailings reclamation measures following closure. An understanding of the potential effects and their consequences on the long-term containment of the tailings and tailings solutions is a prerequisite for the successful design and implementation of close-out measures.

Frost heave features have been reported at the Gunnar and Key Lake tailings sites. Heaving of covers, with attendant disruption in surface drainage, and the potential for 'frost pumping' of pore fluid are identified as items of concern. Substantial depths of frozen tailings have been encountered in the tailings deposit at Rabbit Lake, raising concerns over the possibility of thaw of the tailings and resulting tailings water yield and surface settling.

This report discusses Saskatchewan conditions, presents the available technology for the prediction of frost effects, together with example analyses and a proposed assessment methodology. Three representative sites were selected for evaluation. These are Gunnar, Key Lake and Rabbit Lake.

For each site climatic and tailings deposit data relevant to frost prediction were compiled from available sources, primarily other studies conducted under the National Uranium Tailings Program. These data were used to simulate the thermal conditions and model frost development at each of the three sites.

The ground thermal regime is controlled by heat exchange at the ground surface and heat conduction with depth. Heat exchange at the ground surface is affected by site specific parameters such as vegetation, snow cover and local evaporation, as well as general climatic conditions. Saskatchewan mines are located in areas of discontinuous permafrost, where the balance between permafrost and non-permafrost conditions is quite sensitive. As a result, local ground conditions exert a strong influence upon whether permafrost conditions are favored.

The modeling for all of the sites demonstrated that local permafrost could develop where local conditions were favorable. Thus the frost heave observed at Gunnar and Key Lake can be explained on theoretical grounds. Uncalibrated modeling for Rabbit Lake tailings indicated that thawing was likely with up to 3.5 m of settlement, however, complete thawing could take more than 100 years.

Four different cover types; waste rock, vegetation and two thick, engineered covers were evaluated. The covers (with the exception of the vegetation cover only) will reduce the amount of seasonal freezing of the tailings. The reduction occurs because of the insulating nature of the covers, as well as decreasing the evapotranspiration heat loss during the summer months. The engineered covers almost completely eliminate seasonal freezing and thawing of the tailings, although the cover layers will be subject to frost effects. The vegetation only cover will tend to increase evapotranspiration losses and increase heat losses from the soil.

Pore water expulsion features, such as the hummocks at Key Lake, are a concern because of their height (1 to 1.2 m), and the irregular heave associated with this mechanism, and the tendency to crack and expose the surficial soils. Estimation of the material and drainage conditions under which these features will occur is important in decommissioning design. The theoretical technology for such predictions exists but it is not well developed in practice.

The 'frost pumping' mechanism is speculative at this point in time. Further investigation and research is needed to clarify the significance of this mechanism.

Freezing and thawing increases soil and tailings permeability. The increase occurs because of several mechanisms. If sufficient moisture is available, segregational heave occurs. Even small amounts of heave can create a fissure network that increases soil permeability. Such increases in permeability have been demonstrated at Key Lake. If covers exist in an undersaturated condition, the soil will shrink upon freezing, resulting in a vertical series of cracks that can also affect permeability. The combination of these effects can increase the barrier or tailings permeability by an order of magnitude or more.

The major effect of frost action upon the potential for soil erosion is the formation of expulsive frost boils. Boils such as those at Key Lake can crack the overlying soil and expose the tailings to wind and water erosion. This mechanism is considered to be a major concern in the case of vegetation only cover, a lesser concern with rock only cover and a limited concern for engineered covers.

A benefit of achieving aggrading frost conditions would be that the pore fluid is immobilized, thus preventing it from being released to the environment. The disadvantage is that heaving associated with development of the frost could disrupt surface drainage. It would take a relatively small change in the thermal balance to invoke permafrost aggradation at the Saskatchewan sites. Two basic methods of changing the heat balance were considered. Use of artificial means, such as active refrigeration using heat syphons, may be of limited value because of the long-term care and maintenance required. Changing the surface conditions holds some promise. The use of a convective rock cover has been shown to promote frost aggradation in both natural and artificial situations. This was briefly evaluated using numerical modelling methods. It is concluded that thick (1 to 2 m) rock waste covers of suitable grading may be beneficial in achieving such aggradation at Saskatchewan tailings sites.

A methodology for the investigation of frost action is outlined and reclamation design considerations are discussed.

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CHAPTER 1.0
INTRODUCTION

1.1 GENERAL

Saskatchewan uranium mines are unique in that they are located in northern latitudes (56° to 60° N) where deep seasonal frost and discontinuous permafrost conditions are present. The relationship of the locations of the mines considered in this report (Gunnar, Key Lake and Rabbit Lake) to the permafrost regions in Canada is illustrated on Figure 1.1-1.

1.2 PERMAFROST, CLIMATE AND URANIUM TAILINGS

Permafrost occurs because cold surface air temperatures are reflected in ground temperatures that never rise above 32° F. Since temperature is an index of the level of heat storage, it fluctuates in response to the heat losses and gains at the ground surface. These follow a cyclical pattern on a daily as well as a yearly basis.

Climate is a basic factor in the formation and existence of permafrost. Observations indicate a broad relationship between mean annual air and ground temperatures in permafrost regions. Snow cover is important along with the complex energy exchange regime at the ground surface, causing the mean annual ground temperature to be several degrees warmer than the mean annual air temperature.

Detailed texts on permafrost in Canada and its influence on engineering structures can be found elsewhere (Johnston 1981).

Although tailings impoundments have been developed in northern Canada, frost effects have not been studied in detail. The effects of frost on the potential for contaminant release have been found to be relatively unimportant during the operating life of the impoundment. During this period there is active control of containment and surface releases. Decommissioning of uranium mines poses special concerns arising from potential long-term environmental loadings. For post-closure conditions reliance must be placed on the engineered barriers and control structures installed during operation and reclamation. These measures include covers to prevent infiltration, erosion and seepage.

Steffen Robertson and Kirsten (SRK 1986), discussed the effects of frost action on covers and structures. Frost heaving of covers, with attendant disruption in surface drainage, and the potential for "frost pumping" of pore fluid were identified as items of concern. Frost heaving features have been reported at Gunnar (BBT et al, 1986) and Key Lake (Knight and Piesold 1986). Recent work at Rabbit Lake (Geocon 1987) has identified significant frost as present within the tailings impoundment. Thus there may be concern over the possibility of thaw of the tailings and resulting water yield and tailings surface settlement.

To provide for secure long-term containment it is necessary to anticipate the effects of frost action, and to design and construct close-out measures that make allowance for these effects. This report discusses Saskatchewan conditions, presents the available technology for the prediction of frost effects and presents example analyses and a proposed assessment methodology.

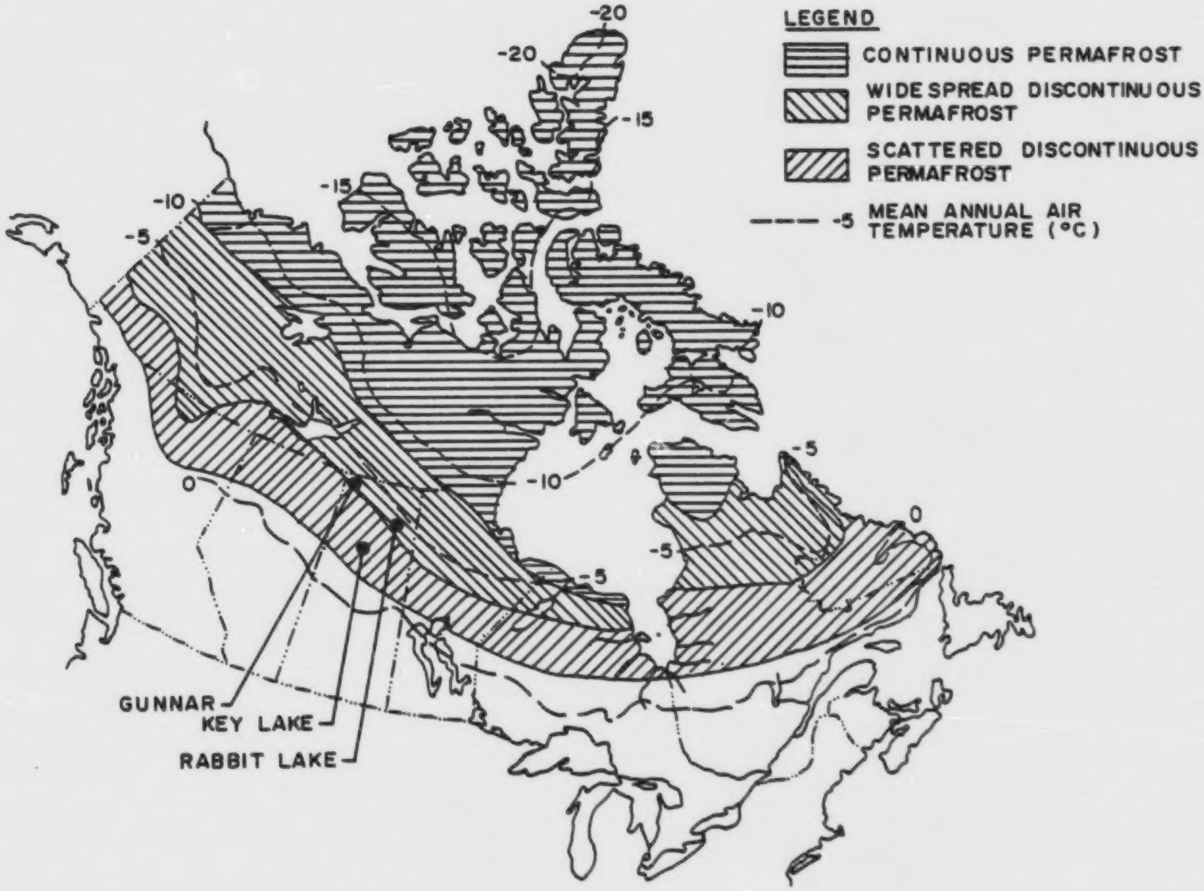

LEGEND
CONTINUOUS PERMAFROST
WIDESPREAD DISCONTINUOUS PERMAFROST
SCATTERED DISCONTINUOUS PERMAFROST
-5 MEAN ANNUAL AIR TEMPERATURE (°C)
-20
-20
-15
-15
-10
-5
-10
-10
-5
0
-5
-5
0
GUNNAR
KEY LAKE
RABBIT LAKE

Figure 1.1-1 The Permafrost Region in Canada (after Brown, 1967)

CHAPTER 2.0
SASKATCHEWAN CONDITIONS

2.1 INTRODUCTION

Three sites typical of northern Canadian mines were selected for review. They are the Gunnar main tailings, Key Lake and Rabbit Lake. All sites are in Saskatchewan and are within the discontinuous permafrost zone.

2.2 GUNNAR TAILINGS

2.2.1 GENERAL

The Gunnar mine site is approximately 25 kilometres southwest of Uranium City, in northwestern Saskatchewan. During its active life from 1955 to 1964, the mine produced approximately 4.4 million tons of tailings that were stored on surface.

Ore was ground to 50% minus 200 mesh (0.074 mm), the uranium was extracted, and the residue discharged as tailings at approximately 30% solids. Following processing, during which sulfuric acid, sodium chlorate, magnesium oxide and sodium chloride were added, tailings were discharged to the Gunnar main tailings basin, formerly Mudford Lake. As the Gunnar main basin filled, the tailings overflowed into the Gunnar central and then the Langley Bay tailings area.

Only the Gunnar main tailings properties are summarized in this report. All of the data was obtained from the BBT (1986) report. Figure 2.2-1 shows the Gunnar layout, and Figure 2.2-2 the Gunnar main tailings area.

2.2.2 CLIMATE

Meteorological data from the Uranium City station were used, since Gunnar meterological data covered only one season. The temperature, precipitation, wind and snow cover data for the period 1951 to 1980 are summarized in Table 2.2-1. Also presented are the calculated freezing/thawing indices and potential evapotranspiration calculated by the Thornthwaite method (Thornthwaite 1948). The meteorological information is summarized on Figure 2.2-3a and 3b.

2.2.3 SITE

The tailings infilled Mudford lake which was a natural depression within Precambrian bedrock terrain. The bedrock highs, surrounding the lake, are sparsely mantled with thin drift, while the bedrock lows are infilled with lacustrine silt and clay. Ponded water is present in the area with the water table approaching ground surface.

2.2.4 TAILINGS PROPERTIES

During tailings deposition the coarse-grained sand was deposited close to the discharge point and the finer grained sand deposited further from the discharge. The location of test holes and approximate boundaries to coarse and fine tailings are shown on Figure 2.2-2. Laboratory classification and volumetric test data is shown in Table 2.2-2 for the coarse tailings, fine tailings and native soil deposits. The average properties are summarized in Table 2.2-3. Figures 2.2-4 to 2.2-6 illustrate the moisture content, density and gradation profiles. In the fine tailings area, there is a surficial layer, approximately 1 m in thickness, which is significantly coarser grained than the underlying tailings. The moisture content and density profiles are relatively constant below a depth of 1 m.

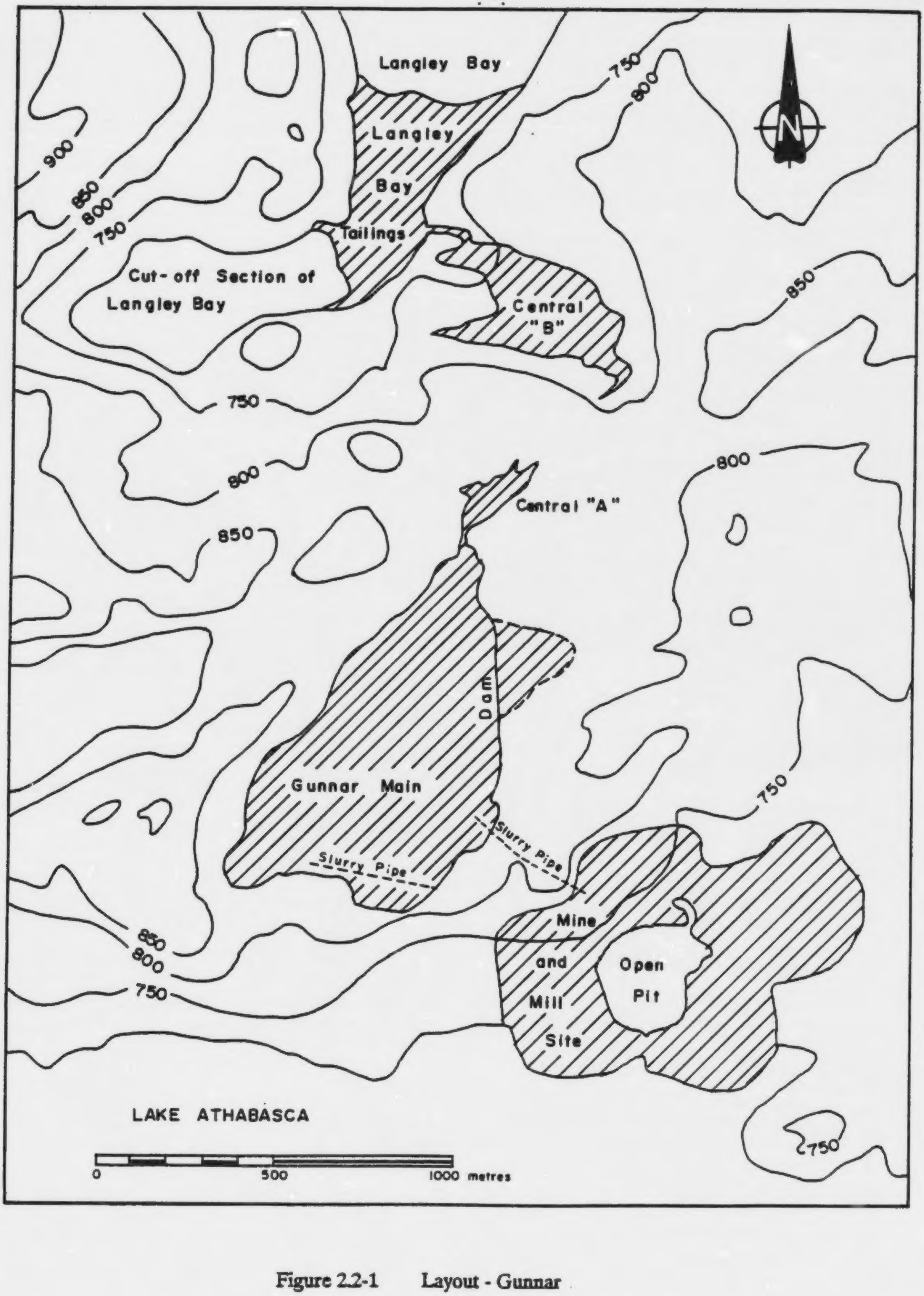
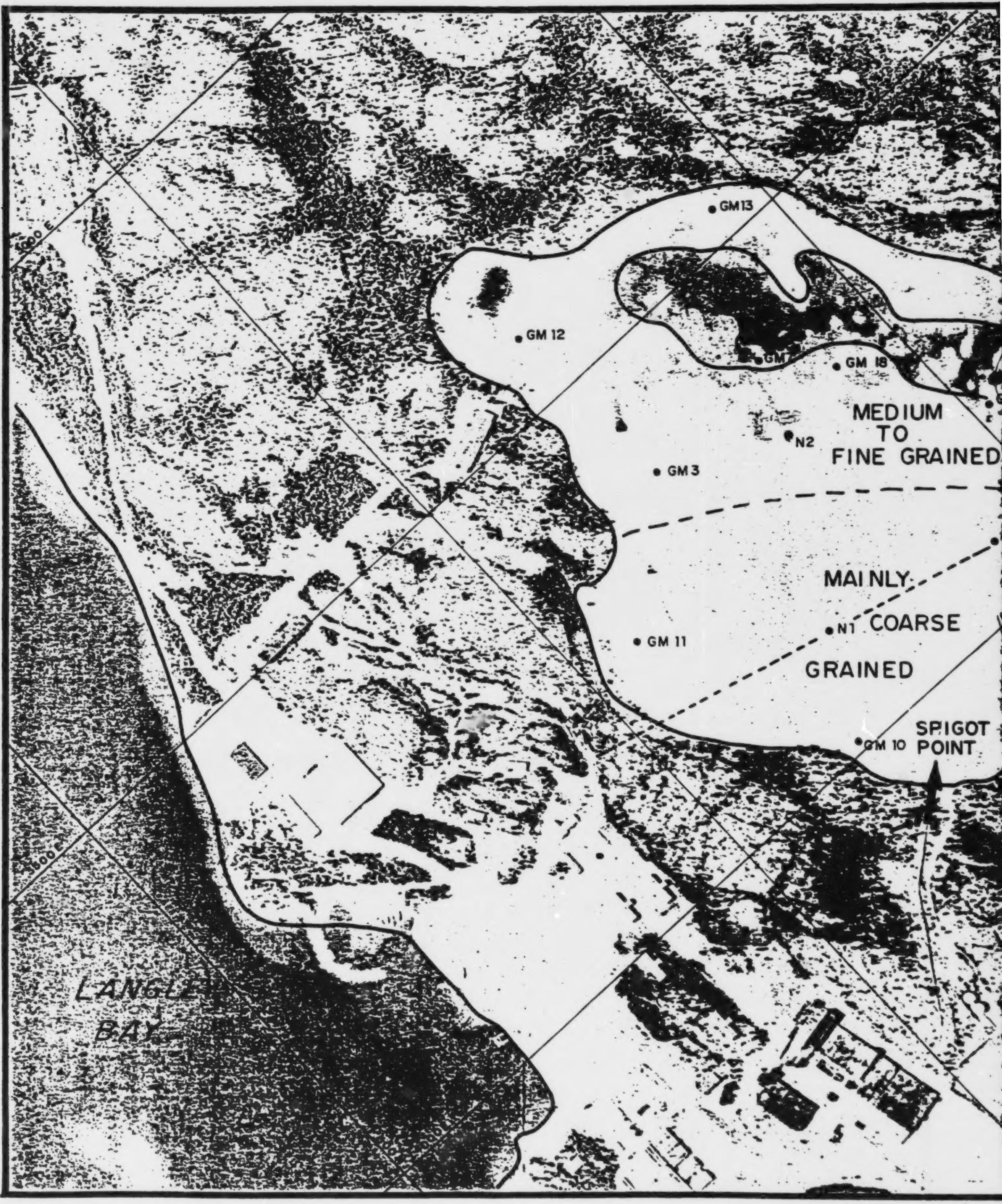
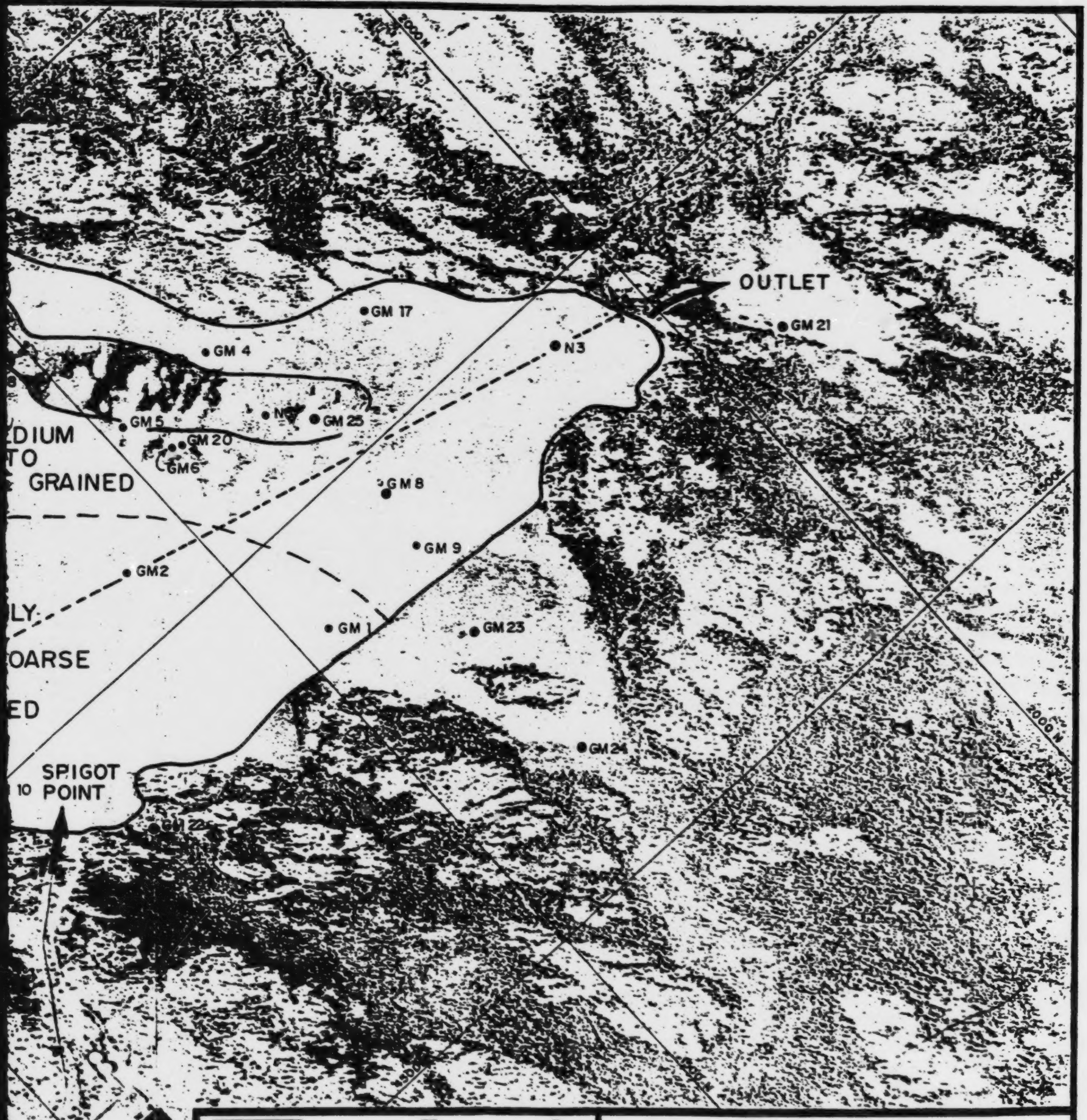

Langley Bay
Langley Bay Tailings
Cut-off Section of Langley Bay
Central "B"
Central "A"
Dam
Gunnar Main
Slurry Pipe
Slurry Pipe
Mine and Mill Site
Open Pit
LAKE ATHABASCA
N
900
850
800
750
0
500
1000 metres

Figure 2.2-1 Layout - Gunnar


GM13
GM 12
GM7
GM 18
MEDIUM
TO
FINE GRAINED
N2
GM 3
MAINLY
COARSE
GRAINED
N1
GM 11
SPIGOT
POINT
GM 10
LANGLE
BAY


2000 N
2000 E
OUTLET
GM 17
GM 21
N3
GM 4
N2
GM 25
GM 5
EDIUM
TO
GRAINED
GM 20
GM 6
GM 8
GM 9
GM 2
LY:
OARSE
ED
GM 1
GM 23
GM 24
2000 N
SPIGOT
POINT
10
GM 22
1000 N

BBT Geotechnical Consultants Ltd.
BBT GEOTECHNICAL CONSULTANTS LTD.

SERGENT, HAUSKINS & BECKWITH
CONSULTING GEOTECHNICAL ENGINEERS
PHOENIX • ALBUQUERQUE • SANTA FE

GUNNAR MAIN TAILINGS

NATIONAL URANIUM TAILINGS PROGRAM
GUNNAR FIELD STUDY
SOUTH OF URANIUM CITY, SASKATCHEWAN

SCALE 1:5000	DRAWN BY W.T.	FIGURE 2.2-2
DATE DEC. '85	APPROVED BY	

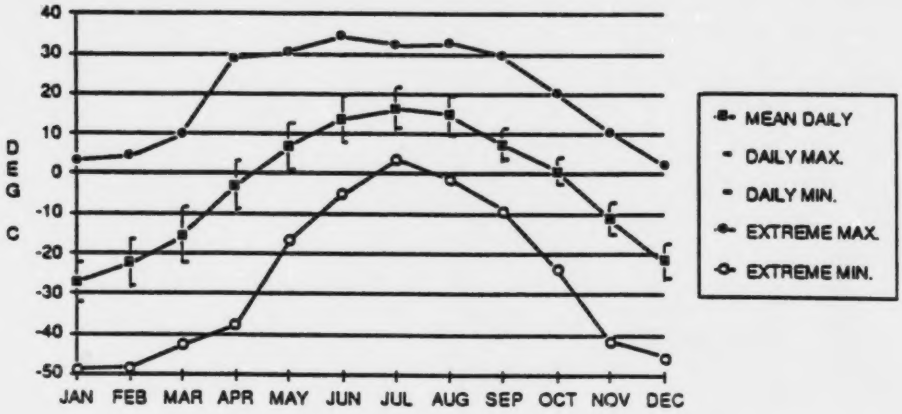
TABLE 2.2-1
GUNNAR METEOROLOGICAL SUMMARY

STATION URANIUM CITY A
PERIOD 1951-1980

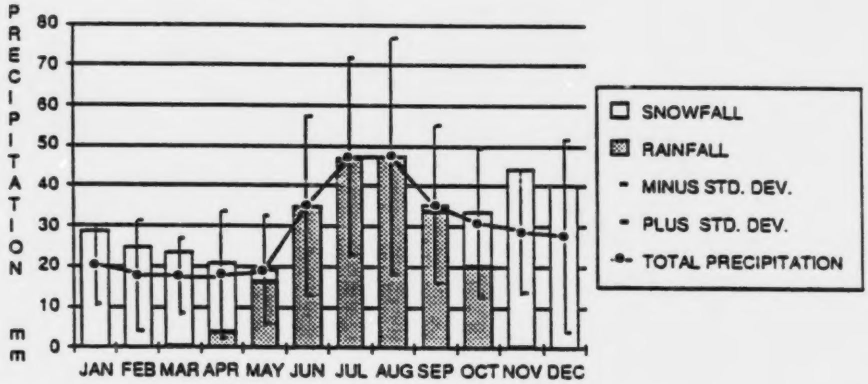
LATITUDE 59 deg 34 min N
LONGITUDE 108 deg 29 min W
ELEVATION 318 m

DATA SECTION		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	ANNUAL
MEAN DAILY MAXIMUM TEMPERATURE	deg C	-22.3	-16.6	-8.6	3	12.5	19.1	21.4	19.5	11.2	4	-7.4	-17.3	1.5
MEAN DAILY MINIMUM TEMPERATURE	deg C	-32.3	-28.4	-22.4	-9.1	0.8	7.8	11	9.6	3.4	-2.7	-15.2	-26.1	-8.6
MEAN DAILY TEMPERATURE	deg C	-27.3	-22.5	-15.5	-3.1	6.7	13.5	16.2	14.6	7.3	0.6	-11.3	-21.7	-3.5
STANDARD DEVIATION, DAILY TEMP.	deg C	3.5	4.2	3.6	3.6	2	1.6	1.3	1.5	1.9	1.9	3.2	3.8	0.9
EXTREME MAXIMUM TEMPERATURE	deg C	3.3	4.4	10	28.9	30.6	34.4	32.2	32.8	29.4	20	10.5	2.2	34.4
EXTREME MINIMUM TEMPERATURE	deg C	-48.9	-48.3	-42.8	-37.8	-16.7	-5	3.7	-1.4	-9.4	-23.9	-41.7	-45.6	-48.9
MEAN RAINFALL	mm	0	0.1	0.2	4	16.2	35	47.3	47.4	34	20	0.6	0.1	204.9
MEAN SNOWFALL	mm water	29.2	24.9	23.7	17	3.2	0.1	0	0	1.8	13.7	43.7	40.6	197.9
MEAN TOTAL PRECIPITATION	mm	20.2	17.7	17.5	17.8	19	35.1	47.3	47.4	35.4	30.8	28.8	27.8	344.8
STD. DEVIATION, TOTAL PRECIPITATION	mm	9.8	13.6	9.3	15.7	13.5	22.3	24.5	29.2	19.4	18.5	15.4	23.8	65.4
MEAN WIND SPEED	km/hr	8.6	9.2	10.9	12.3	13.2	12.4	11.4	11.4	12.4	12.4	11.6	9.2	11.3
PREVAILING DIRECTION		ENE	ENE	ENE	ENE	E	ENE	ENE	ENE	ENE	E	E	ENE	ENE
MEDIAN DEPTH OF SNOW COVER	mm	292	249	237	17	3				18	137	437	406	
SOLAR RADIATION	W/sq. m	22.00	62.00	127.00	218.00	276.00	266.00	297.00	195.00	109.00	63.00	24.00	16.00	
DERIVED SECTION														
FREEZING INDEX	deg C days	760	667	445	108						39	333	633	3004
THAWING INDEX	deg C days				5	190	390	470	417	221	35			1727
		FREEZING		THAWING										
PERIOD	days	190		175										
STEP TEMPERATURE	days	-15.8		9.9										
POTENTIAL EVAPOTRANSPIRATION	mm	0	0	0	0	60	108	126	106	51	6	0	0	457
NET WATER BALANCE	mm	20	18	18	18	-41	-73	-79	-58	-16	25	29	28	-112

TEMPERATURE



PRECIPITATION



MEAN WIND SPEED AND PREVAILING DIRECTION

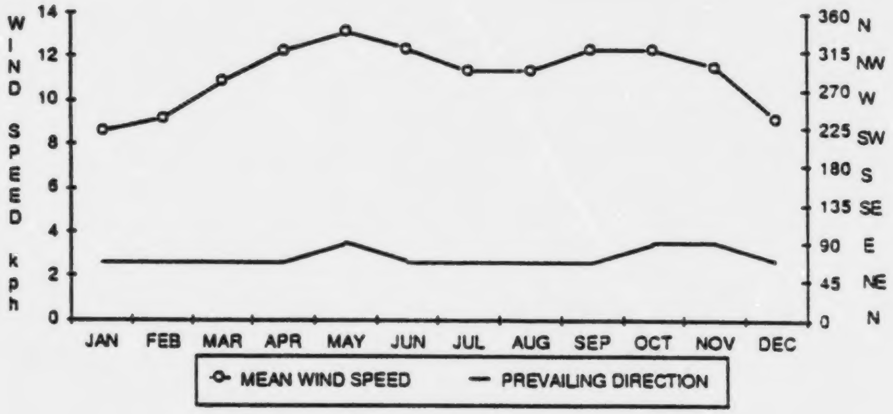
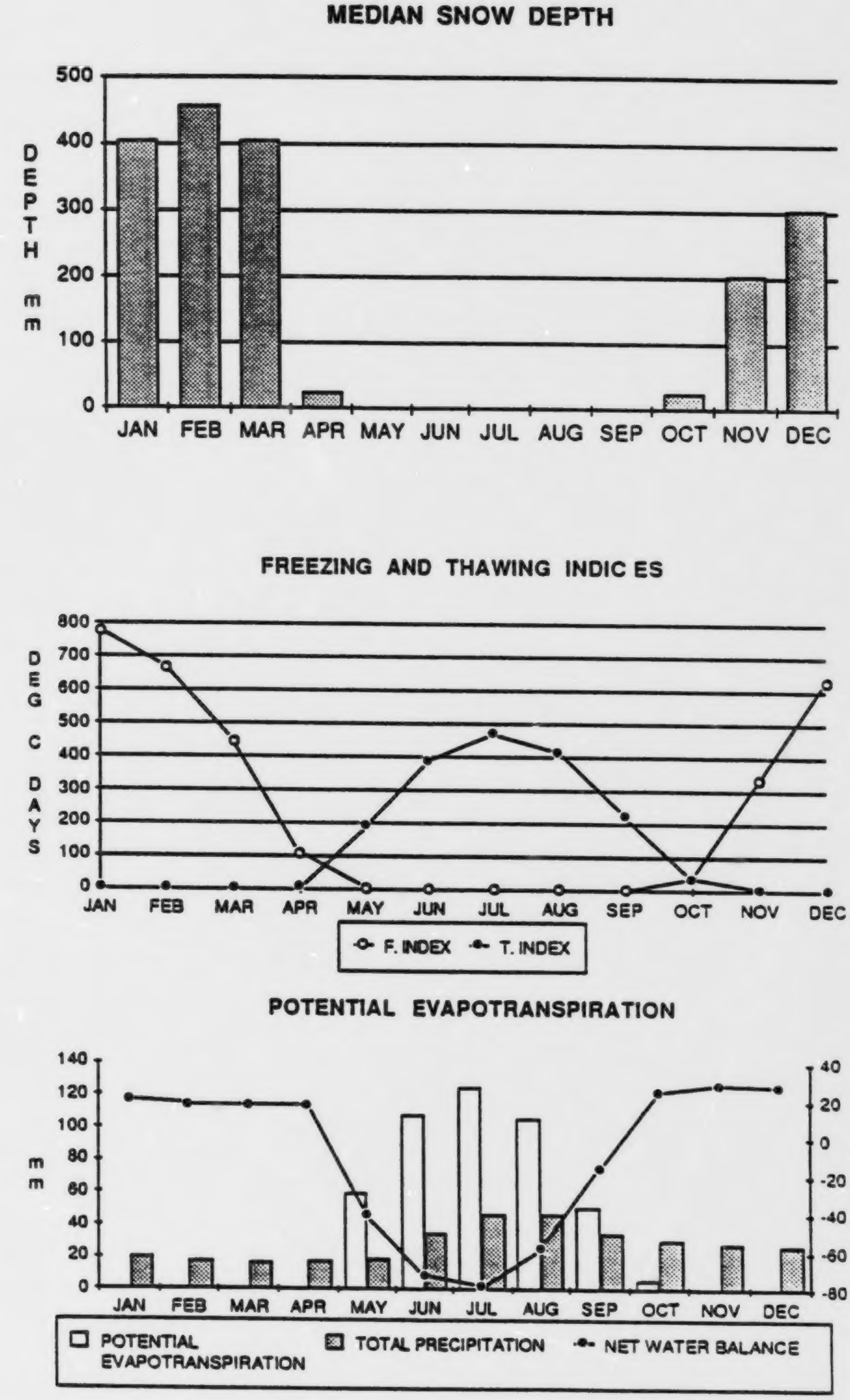


Figure 2.2-3a Uranium City Meteorological Summary



MEDIAN SNOW DEPTH

FREEZING AND THAWING INDIC ES

POTENTIAL EVAPOTRANSPIRATION

Figure 2.2-3b Uranium City Meteorological Summary

TABLE 2.2-2
GUNNAR MAIN SOIL PROPERTIES

GROUP	LOCATION	DEPTH	USC CLASS	SOIL TYPE	MOISTURE CONTENT	PLASTIC LIMIT	LIQUID LIMIT	SPECIFIC GRAVITY	FIELD DENSITY	VOID RATIO		DEGREE OF SATURATION	GRADATION				LAB PERMEABILITY
										FROM WC	FROM DENS.		M. SAND	F. SAND	SILT	CLAY	
		m			%	%	%		kg/cu m			%	%	%	%	%	cm/sec
COARSE TAILINGS																	
2	GM10A-S1	0	SP	TA	10.6					0.284			22	66	12	0	
2	GM11A-S1	0	SP	TA	5.5					0.147			45	48	7	0	
2	GM1A-S1	0	ML	TA	27.2					0.729			6	46	42	10	
2	GM2A-S1	0	SP	TA	8.1					0.217			16	70	12	2	
2	GM2A-S4	3	SP	TA	26.5				1519	0.710	0.764	17	2	86	8	4	7.50E-06
2	GM2A-S6	5.5	SM	TA	23.6				1673	0.632	0.602	36	8	70	17	5	2.70E-04
2	GM2A-S7	6.1	SM	TA	18.1				1668	0.485	0.607	117					
2	GM2D-S1	0.3		TA	4.9				1361	0.131	0.969	65					
2	GM2D-S2	0.6		TA	4.7				1343	0.126	0.996	49					
2	GM2D-S3	0.9		TA	14.3				1278	0.383	1.097	12					
2	GM2D-S4	1.2		TA	7				1324	0.188	1.024	12					
2	N1A-S1	3.7	SM	TA	15.6				1489	0.418	0.800	0	2	72	24	4	4.70E-04
2	N1A-S2	6.7	ML	TA	14.2					0.381							
2	N1B-S3	5.2	SM	TA	8.9					0.239							
2	N1C-S1	0	SM	TA	8.2				1410	0.220	0.901	42	10	64	24	2	
2	N1C-S2	1.5	SM	TA	7.1				1037	0.190	1.584	15	6	70	21	3	1.10E-03
2	N1C-S3	3	SM	TA	8.4	NP	NP	2.596	1350	0.225	0.985	22	2	72	24	2	
2	N1C-S4	4.6	SM	TA	12.8					0.343							
2	N1C-S5	6.1	SM	TA	13.2	NP	NP	2.65	1669	0.354	0.606	37	0	64	32	4	
2	N1C-S6	7.6	SM	TA	17.2				1574	0.461	0.703	49	4	70	24	2	
2	N1C-S7	9.1	SM	TA	15.4				1664	0.413	0.611	58	12	68	16	4	
2	N1C-S7D	9.1	SM	TA	16.1					0.431			12	68	15	5	
2	N1C-S8	14.8	SM	TA	14.8				1652	0.397	0.622	66	8	68	22	2	
2	N1C-S9	11.3	SM	TA	14.9				1380	0.399	0.942	46	2	50	47	1	1.10E-04
2	N1C-S9D	11.3	SM	TA	21.6					0.579							4.40E-06
2	N1D-S1	3.1	SM	TA	7.6	NP	NP	2.719	1719	0.204	0.559	71	0	76	19	5	1.80E-03
2	N1E-S1	0	SM	TA	8.3				1226	0.222	1.186	49	6	50	34	10	
2	N1E-S10	4.6	SM	TA	10.9			2.707	1459	0.292	0.837	24	4	64	24	8	8.70E-04
2	N1E-S12	6.1	SM	TA	17.1				1750	0.458	0.531	42					
2	N1E-S13	8.6	SM	TA	18.5				2027	0.496	0.322	91	6	74	15	5	
2	N1E-S14	9.2	SP	TA	14.9				1854	0.399	0.446	103	2	76	14	8	6.60E-05
2	N1E-S17	13.4	ML	TA	15.8					0.423			0	30	60	10	
2	N1E-S4	1.5	SP	TA	3.9					0.105			14	72	9	5	
2	N1E-S6	2.1	SP	TA	5.5	NP	NP		1590	0.147	0.686	62	12	64	19	5	1.10E-03
2	N1E-S8	2.8	SP	TA	7.3				1410	0.196	0.901	12					
2	N1E-S9	4.2	SM	TA	8.6			2.678	1610	0.230	0.865	22	2	63	32	3	8.20E-05
AVERAGE					12.7			2.670	1521.4	0.340	0.798	45	8	65	23	4	1.72E-04

NOTE: USC symbols as follows:

SP	Poorly graded sand	TA	Tailings
SM	Silty sand	NA	Native Soil
ML	Low plasticity silt		
CL	Low plasticity clay		
OL	Low plasticity organic silt	NP	Non-plastic

TABLE 2.2-2
GUNNAR MAIN SOIL PROPERTIES

GROUP	LOCATION	DEPTH	USC CLASS	SOIL TYPE	MOISTURE CONTENT	PLASTIC LIMIT	LIQUID LIMIT	SPECIFIC GRAVITY	FIELD DENSITY	VOID RATIO		DEGREE OF SATURATION	GRADATION				LAB PERMEABILITY
										FROM WC	FROM DENS.		M. SAND	F. SAND	SILT	CLAY	
		m			%	%	%		kg/cu m			%	%	%	%	%	cm/sec
FINE TAILINGS																	
1	GM12A-S2	1.2	ML	TA	53.1	24.8	32.3			1.423			0	16	76	8	
1	GM13A-S1	0	ML	TA	33.2					0.890			0	2	94	4	
1	GM13A-S2	1.6	ML	TA	28.6			2.779	1031	0.766	1.599	30					
1	GM13A-S3	3	ML	TA	28.6	21	23.8		1220	0.766	1.197	74	0	22	76	2	
1	GM13A-S5	6.1	CL	TA	40.7	22.3	31.2		1308	1.091	1.049	73	0	8	82	10	2.10E-07
1	GM17A-S6	0	ML	TA	42.6					1.142			0	6	84	10	
1	GM18A-S1	0	SM	TA	26.1					0.699			2	58	36	4	
1	GM19A-S3	0	ML	TA	31.4					0.842			0	16	76	8	
1	GM20-S1	0.3		TA	4.7				1327	0.126	1.020	83					
1	GM20-S2	0.6		TA	4.5				1384	0.121	0.936	78					
1	GM20-S3	0.9		TA	4.8				1409	0.129	0.902	14					
1	GM3A-S1	0	SP	TA	7.9					0.212			22	62	15	1	
1	GM3A-S3	2.4	ML	TA	22.7			2.687	1696	0.608	0.581	32	0	50	42	8	2.20E-04
1	GM3A-S4	3.3	SM	TA	24.1			2.672	1556	0.646	0.722	29	0	80	15	5	5.40E-04
1	GM3A-S7	6.1	SM	TA	19.5				1697	0.523	0.579	105					2.60E-04
1	GM3A-S8	8.6	ML	TA	24.6				1634	0.659	0.640	101	2	38	55	5	
1	GM3A-S9	9.1	SM	TA	28.2				1509	0.756	0.776	67					
1	GM4A-S1	0	ML	TA	36.5					0.978			1	8	84	7	
1	GM4A-S2	0.6	SM	TA	14.7				1245	0.394	1.153	66					
1	GM5A-S1	0	SP	TA	15.4					0.413			5	71	21	3	
1	GM6A-S4	4.2	ML	TA	32.6					0.874			0	18	74	8	
1	GM6A-S5	7.8	ML	TA	33.5					0.898			0	30	64	6	
1	GM6C-S1	0.15		TA	10.8				1197	0.289	1.239	71					
1	GM6C-S2	0.3		TA	26.3				1085	0.705	1.470	61					
1	GM6C-S3	0.6		TA	16.3				1213	0.437	1.209	24					
1	GM6C-S4	0.9		TA	28.3				1235	0.758	1.170	60					
1	GM6C-S5	1.2		TA	28				1400	0.750	0.914	46					
1	GM7A-SI		SM	TA	37.1					0.994			4	60	28	8	
1	GM8A-S1	0	SP	TA	16.7					0.448			14	58	26	2	
1	GM8A-S1D	0	SP	TA						0.000							
1	GM9A-S3	4.1	CL	TA	19.6	15.5	28.9		1632	0.525	0.642	70	2	9	60	30	8.30E-07
1	N2A-S1	2.1	ML	TA	65.4					1.753							
1	N2A-S2	4.9	SM	TA	20.8					0.557			0	43	53	4	
1	N2B-S3	3	ML	TA	28.2					0.756			1	19	78	2	
1	N2C-S4	1.5	SM	TA	25.6					0.686			0	46	53	1	
1	N2C-S4D	1.5	SM	TA	22.5	NP	NP			0.603			2	52	40	6	
1	N2D-S5	0.6	SM	TA	24.4					0.654			4	55	38	3	
1	N2E-S1	0	SP	TA	6.2					0.166			30	60	8	2	
1	N2E-S10	7.6	ML	TA	21.9	18.2	19		1642	0.587	0.632	103	1	47	50	2	
1	N2E-S4	2.4	SM	TA	21.3	NP	NP		1660	0.571	0.614	338	2	64	31	3	
1	N2E-S6	3.4	ML	TA	19.5				1726	0.523	0.553	182	0	44	51	5	
1	N2E-S7	4.6	SM	TA	19.8	NP	NP		1725	0.531	0.554	103	2	72	20	6	1.90E-04
1	N2E-S8	5.5	SM	TA	22.9			2.679	1749	0.614	0.532	98					3.20E-04
1	N2E-S9	6.1	SM	TA	19.1	NP	NP		1646	0.512	0.628	84	1	49	50	0	1.40E-06
1	N6A-S1	0.8	SM	TA	21.5					0.576			2	48	42	8	
1	N6A-S2	1.5	SM	TA	40.4					1.063							
1	N6A-S3	4.5	ML	TA	21.1					0.565			1	31	61	7	
AVERAGE					24.8			2.704	1455	0.651	0.888	83	3	40	51	6	2.87E-05

TABLE 2.2-2
GUNNAR MAIN SOIL PROPERTIES

GROUP	LOCATION	DEPTH	USC CLASS	SOIL TYPE	MOISTURE CONTENT	PLASTIC LIMIT	LIQUID LIMIT	SPECIFIC GRAVITY	FIELD DENSITY	VOID RATIO		DEGREE OF SATURATION	GRADATION				LAB PERMEABILITY
										FROM WC	FROM DENS.		M. SAND	F. SAND	SILT	CLAY	
		m			%	%	%		kg/cu m			%	%	%	%	%	cm/sec
NATIVE CLAY																	
1	GM12A-S4	3.4	CL	NA	17.8				1277	0.477	1.099	13					
1	GM13A-S6	7.6	ML	NA	50.3	32	46.1		1099	1.348	1.439	53	2	1	90	7	
1	N2E-S12	9.1	SM	NA	38.7	NP	NP		1384	1.037	0.936	18					
1	N2E-S14	12.2	ML-OL	NA	77.6	31	41.7		904	2.080	1.965	30					
1	N2E-S16	19	CL	NA	37.6	21.8	33.2	2.681		1.008							
3	N3E-S10	8.2	CL	NA	39.6	21.9	31.7	2.714	1278	1.061	1.100	56	2	8	53	37	
3	N3E-S11	10.7	CL	NA	36.7					0.984							
3	N3E-S12	11.3	CL	NA	30.7					0.823							
3	N3E-S13	12.8	CL	NA	39.6	20.8	30.1			1.061							
3	N3E-S14	13.7	CL	NA	35.5					0.951							
3	N3E-S7	5.2	ML-OL	NA	41.4	23	27.9			1.110							
3	N3E-S8	6.1	CL	NA	35.3					0.946							
3	N3E-S9	7	CL	NA	38.4				1229	1.029	1.181	94					
3	N3F-S1	7.3	CL	NA	29.9	18.1	32.9		1473	0.801	0.819	115	3	5	52	40	7.20E-06
1	N6A-S5	6.1	ML	NA	20.7	22.2	24.1		1594	0.555	0.681	159	0	15	79	6	7.40E-07
1	N6A-S7	8.5	CL	NA	36	21.9	41		1387	0.965	0.932	61					5.70E-10
AVERAGE					37.9	23.6	34.3	2.698	1291	1.015	1.126	67	2	7	69	23	1.45E-07

TABLE 2.2-3
GUNNAR MATERIALS SUMMARY

	COARSE TAILINGS	FINE TAILINGS	NATIVE CLAY	NATIVE ROCK
Depth (m)	0-9	0-9	9-14	14+
Depth to water table (m)	4	1.5	-	-
Moisture content (%)	12.7	22.7	30	4
Plastic Limit (%)	*NP	NP	24	-
Liquid Limit (%)	NP	NP	35	-
Specific Gravity	2.67	2.70	2.68	2.7
Dry Density (kg/m^3)	1520	1460	1390	2600
Void Ratio (Calc.)	0.7	0.8	1.13	-
Gradation				
Sand %)	73	43	9	
Silt (%)	23	51	69	
Clay (%)	4	6	23	
D_{10} (mm)		0.13	0.043	
D_{30} (mm)		0.05	0.014	
D_{60} (mm)		0.015	0.002	
Permeability (m/s)		1.7×10^{-6}	2.8×10^{-7}	4×10^{-9}
Coefficient of Compressibility (m^2/kN)	0.04	-	-	-
Pore Water TDS (mg/L)	5000	5000	1900	1900

*NP = non-plastic

In the coarse tailings areas the water table is at depth. There is a general increase in water content and dry density to a depth of about 5 m with relatively constant conditions below 5 m. The gradation is variable with increasing silt content below 11 m.

The void ratio was calculated from water content and density tests below the water table, and density tests only above the water table. There is considerable scatter in calculated saturation below the water table, which suggests some error in density measurements as discussed by BBT (1986).

A single consolidation test was carried out on coarse-grained tailings. The compression index (C_c) is approximately 0.04. The results are not likely representative of fine-grained tailings.

2.2.5 GROUND TEMPERATURES

Frost boil features were observed at several locations in the fine grained tailings where the water table was shallow. These features had a raised surface expression of approximately 1 m and consisted of a permafrost core to a depth of about 5 to 6 m. They were characterized by extreme lateral variability in ground frost conditions with progression from permafrost to non-permafrost conditions within a few metres laterally.

The presence of ground frost is summarized in Table 2.2-4. The information was taken from test hole logs where ground frost was described. In March, the depth of frost in fine tailings varied from 0.6 to 4.4 m with a predominant depth of about 0.8 m. In August, one test pit in fine-grained soil had a thaw depth of 1.3 m. Permafrost was encountered at site N2 from a depth of 3.7 to 4.8 m.

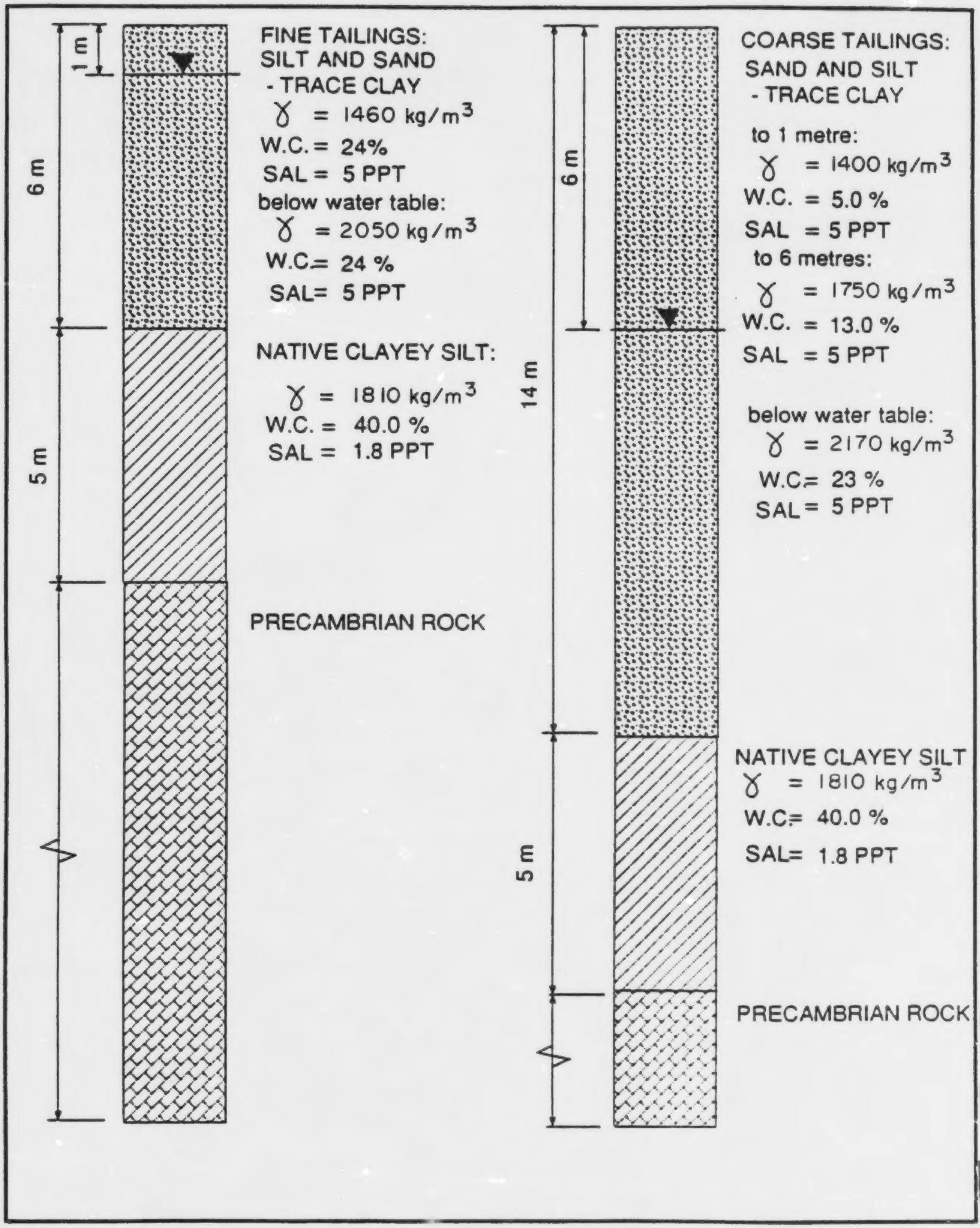

1 m
6 m
5 m
FINE TAILINGS:
SILT AND SAND
- TRACE CLAY
γ = 1460 kg/m3
W.C. = 24%
SAL = 5 PPT
below water table:
γ = 2050 kg/m3
W.C.= 24 %
SAL= 5 PPT
NATIVE CLAYEY SILT:
γ = 1810 kg/m3
W.C. = 40.0 %
SAL = 1.8 PPT
PRECAMBRIAN ROCK
6 m
14 m
5 m
COARSE TAILINGS:
SAND AND SILT
- TRACE CLAY
to 1 metre:
γ = 1400 kg/m3
W.C. = 5.0 %
SAL = 5 PPT
to 6 metres:
γ = 1750 kg/m3
W.C. = 13.0 %
SAL = 5 PPT
below water table:
γ = 2170 kg/m3
W.C.= 23 %
SAL= 5 PPT
NATIVE CLAYEY SILT
γ = 1810 kg/m3
W.C.= 40.0 %
SAL= 1.8 PPT
PRECAMBRIAN ROCK

Figure 2.2-4 Gunnar Stratigraphic Column

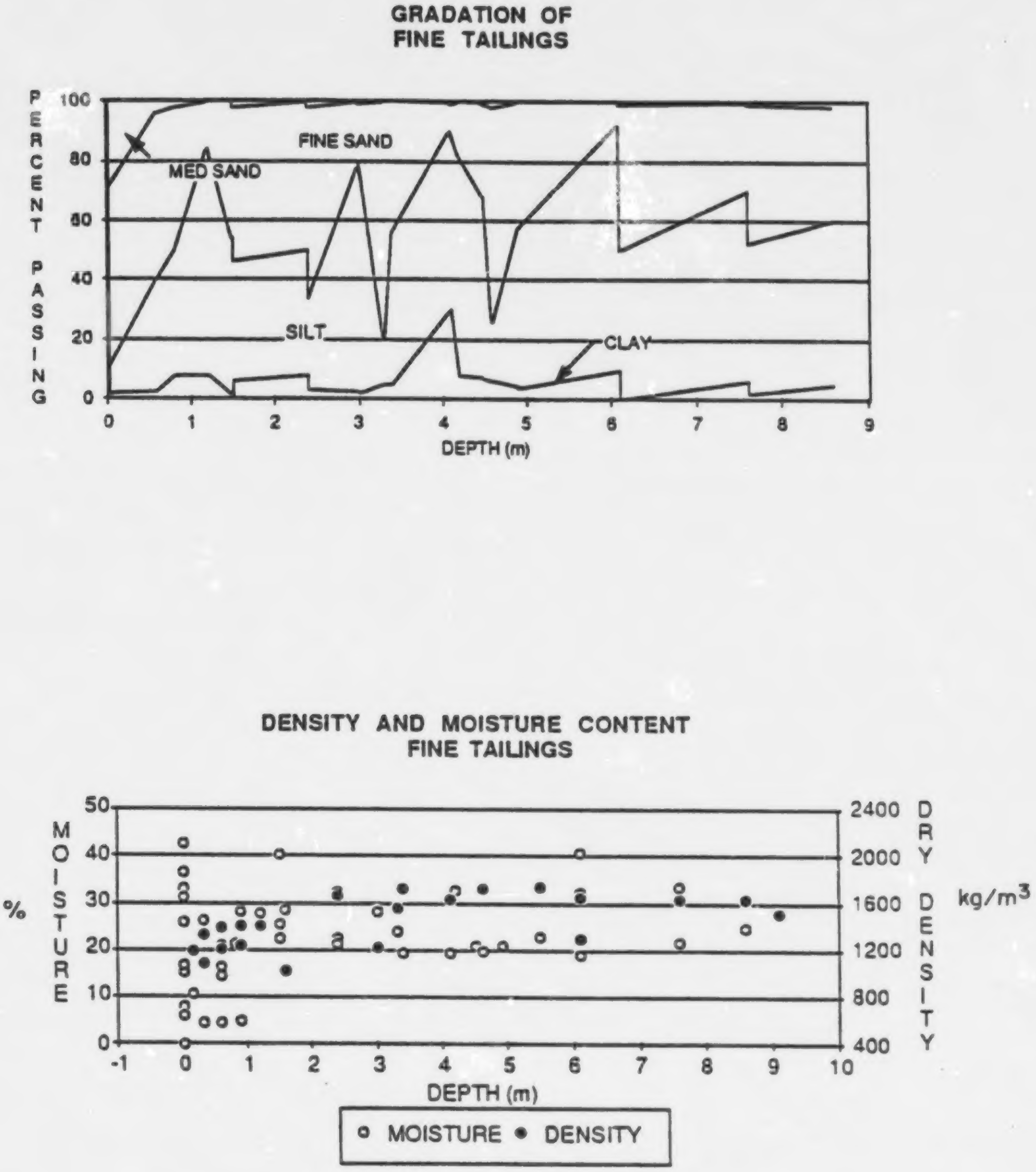
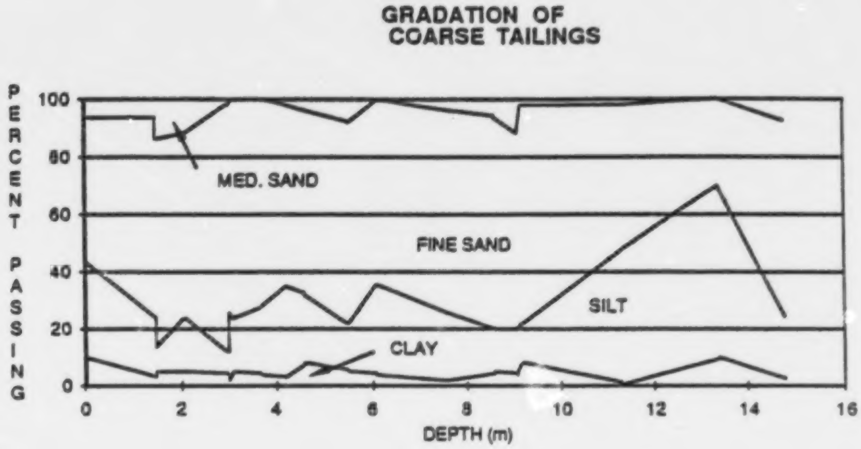


Figure 2.2-5 Fine Grained Tailings Properties



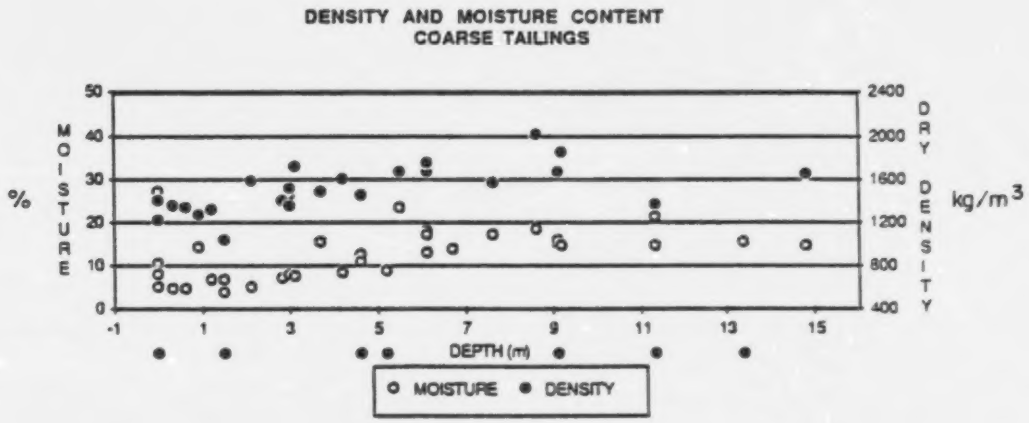


Figure 2.2-6 Coarse Grained Tailings Properties

TABLE 2.2-4
SUMMARY OF GROUND FROST DEPTH

LOCATION	DATE	LAYER 1		LAYER 2	
		From	To	From	To
		m		m	
GM12A-2	20 March 1985	0	0.7		
GM13A-1	19 March 1985	0	0.6		
GM17A-6	12 March 1985	0	4.4		
GM19A-3	12 March 1985	0	1		
GM20-1	1 August 1985	1.3	?		
GM2A-1	29 March 1985	0	1.1		
GM3A-1	28 March 1985	0	0.7		
GM4A-1	12 March 1985	0	1		
GM6A-4	14 March 1985	0	4.3		
GM9A-3	10 March 1985	0	1.8		
N1A-1	1 December 1984	0	2.74		
N1E-1	10 December 1984	0	0.6		
N2A-1	2 December 1984	0	0.9	3.7	4.8
N2E-1	21 March 1985	0	0.7		
N6A-1	9 March 1985	0	2		

Thermister cables were installed at several locations identified on Figure 2.2-2. The temperature profiles are reported by BBT (1986). The validity of the temperatures measured in those cables which were installed inside standpipes with no packing to prevent convective air currents are questionable. Ground temperatures consistent with permafrost or very deep seasonal frost were encountered in GM2A.

2.2.6 HYDROGEOLOGIC PROPERTIES

The total dissolved solids in the tailings pore water is plotted with depth on Figure 2.2-7. The water in the tailings is highly mineralized with a TDS of approximately 5,000 milligrams per litre mostly as Mg and Ca sulphates. The water in the native silt and clay has a total dissolved solids of approximately 1900 milligrams per litre.

The permeability of the materials was determined by laboratory and in situ tests. The results are summarized in Table 2.2-2 and on Figure 2.2-8.

2.3 KEY LAKE

2.3.1 GENERAL

The Key Lake mine is located in north central Saskatchewan (56°12′ N latitude, 105°40′ W longitude).

2.3.2 CLIMATE

Meteorological data from the Cree Lake station were used. The temperature, precipitation, wind and snow cover data for the period 1951 to 1980 are summarized in Table 2.3-1. Also presented are the calculated freezing/thawing indices and potential evapotranspiration calculated by the Thornthwaite method. The meteorological conditions are summarized on Figure 2.3-1a and 1b.

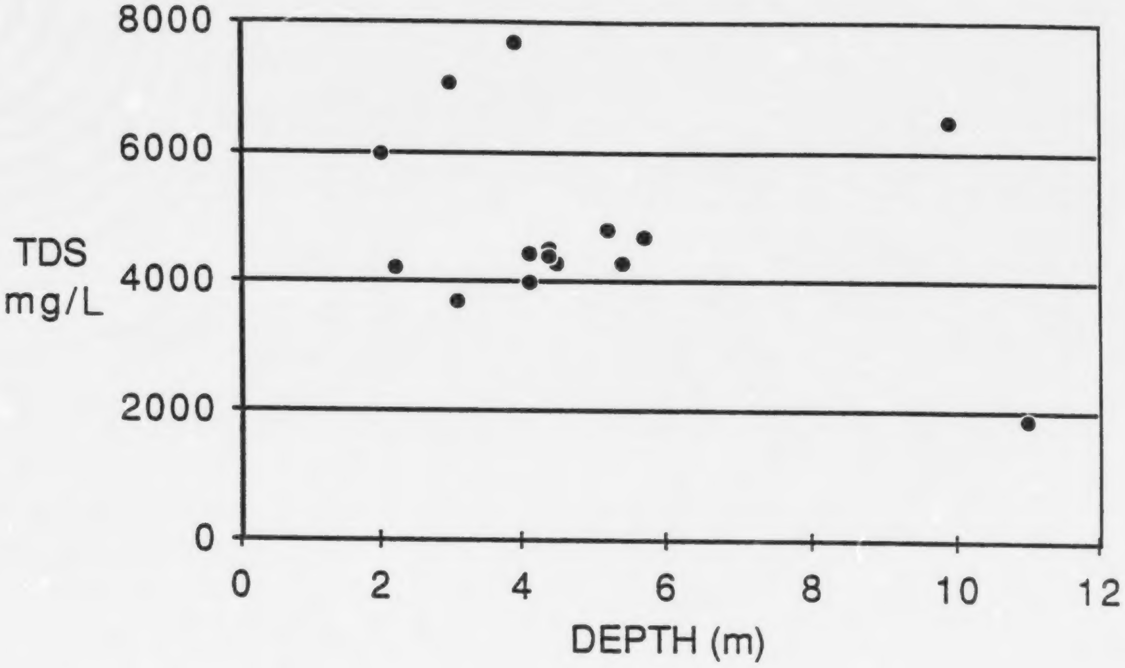


Figure 2.2-7 Pore Fluid TDS Versus Depth

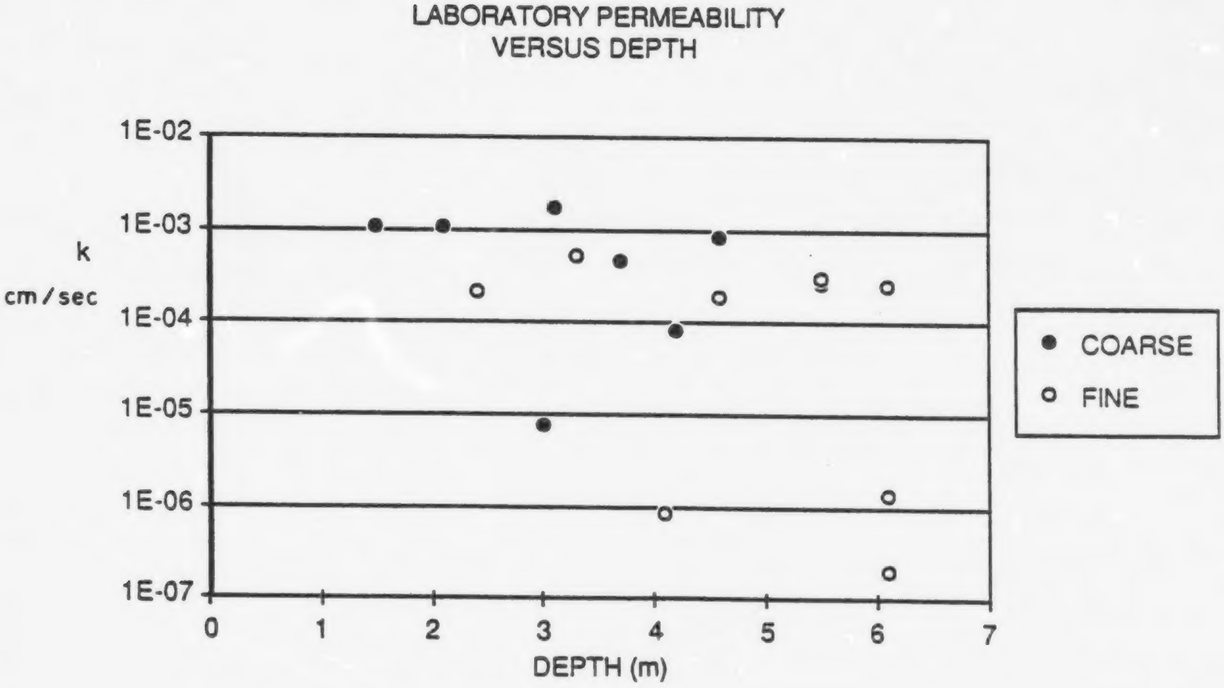


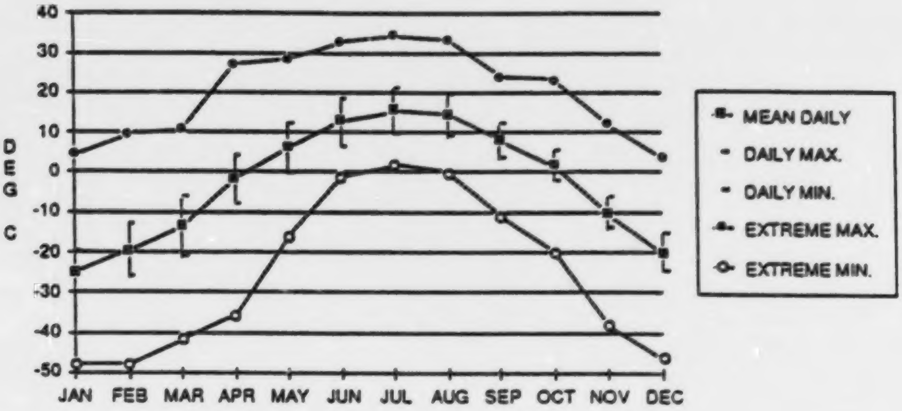
Figure 2.2-8 Permeability Summary.

TABLE 2.3-1
KEY LAKE METEOROLOGICAL SUMMARY

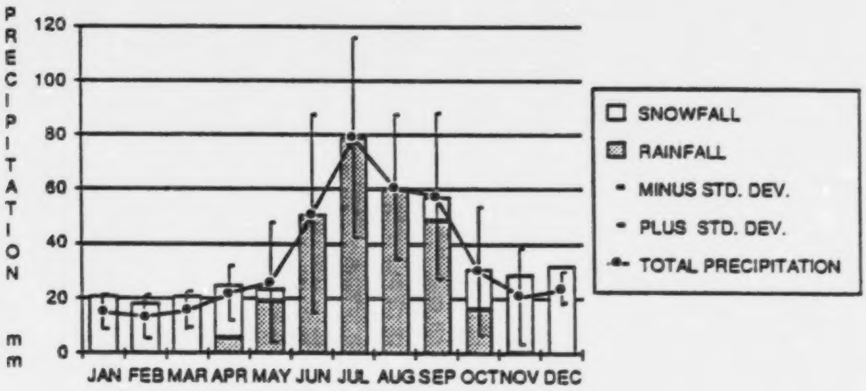
STATION	CREE LAKE	LATITUDE	57 deg 21 min N
PERIOD	1951-1980	LONGITUDE	107 deg 08 min W
		ELEVATION	497 m

DATA SECTION		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	ANNUAL
MEAN DAILY MAXIMUM TEMPERATURE	deg C	-19.8	-13.1	-6.5	4.2	12.3	18.6	21	19.3	11.9	5.3	-6.3	-15.4	2.6
MEAN DAILY MINIMUM TEMPERATURE	deg C	-30.2	-26.1	-21.3	-8.1	-0.4	6.5	9.6	8.9	3.5	-2.2	-14.1	-24.7	-8.2
MEAN DAILY TEMPERATURE	deg C	-25.1	-19.7	-13.6	-1.8	6.1	12.9	15.6	14.4	7.9	1.6	-10.4	-20.1	-2.7
STANDARD DEVIATION, DAILY TEMP.	deg C	2.9	5.2	3.1	3.2	2.2	0.9	1.4	1.9	2.3	1.8	3	4.2	1
EXTREME MAXIMUM TEMPERATURE	deg C	4.4	9.4	10.6	26.9	28.3	32.8	34.4	33.3	23.9	23.1	12	3.6	34.4
EXTREME MINIMUM TEMPERATURE	deg C	-47.8	-47.8	-41.7	-35.7	-16.1	-1.3	1.8	-0.4	-11.1	-20	-38.3	-46.4	-47.8
MEAN RAINFALL	mm	0.2	0.2	0.2	6	19.1	50.5	79.1	60.5	49.1	16.1	0.6	0.1	281.7
MEAN SNOWFALL	mm water	20.9	18	21.1	18.8	4.3	0.4	0	0	8	14.8	28.1	32.4	202.3
MEAN TOTAL PRECIPITATION	mm	14.8	13.4	15.6	21.7	25.8	50.8	79.1	60.5	57.3	30.1	20.9	23.8	413.8
STD. DEVIATION, TOTAL PRECIPITATION	mm	6.3	7.9	6.7	9.8	21.6	36.4	36.6	26.4	30.2	23.3	17.4	5.7	78
MEAN WIND SPEED	km/hr	8.6	9.2	10.9	12.3	13.2	12.4	11.4	11.4	12.4	12.4	11.6	9.2	11.3
PREVAILING DIRECTION		ENE	ENE	ENE	ENE	E	ENE	ENE	ENE	ENE	E	E	ENE	ENE
MEDIAN DEPTH OF SNOW COVER	mm	209	180	211	188	43	4			8	148	281	324	
SOLAR RADIATION	W/sq. m	31.00	74.00	143.00	218.00	262.00	266.00	254.00	203.00	120.00	67.00	31.00	22.00	
DERIVED SECTION														
FREEZING INDEX	deg C days	714	588	387	77						26	303	585	2682
THAWING INDEX	deg C days				9	179	372	453	412	238	51			1713
		FREEZING		THAWING										
PERIOD	days	185		180										
STEP TEMPERATURE	days	-14.5		9.5										
POTENTIAL EVAPOTRANSPIRATION	mm	0	0	0	0	56	105	123	105	55	13	0	0	458
NET WATER BALANCE	mm	15	13	16	22	-31	-54	-44	-45	2	17	21	24	-44

TEMPERATURE



PRECIPITATION



MEAN WIND SPEED AND PREVAILING DIRECTION

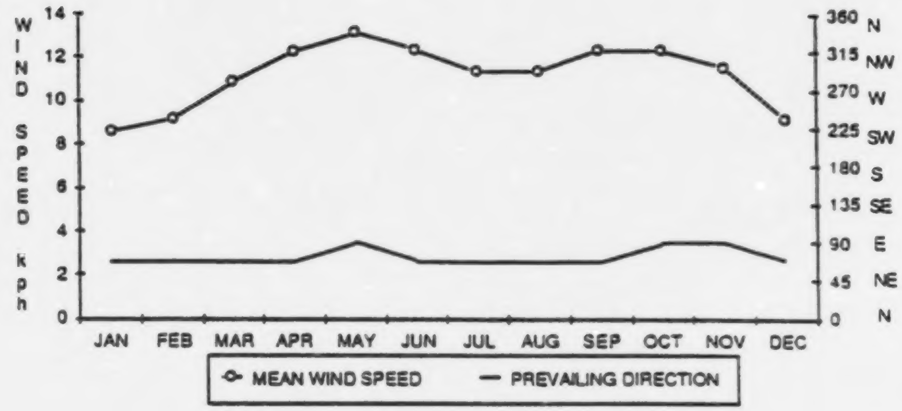
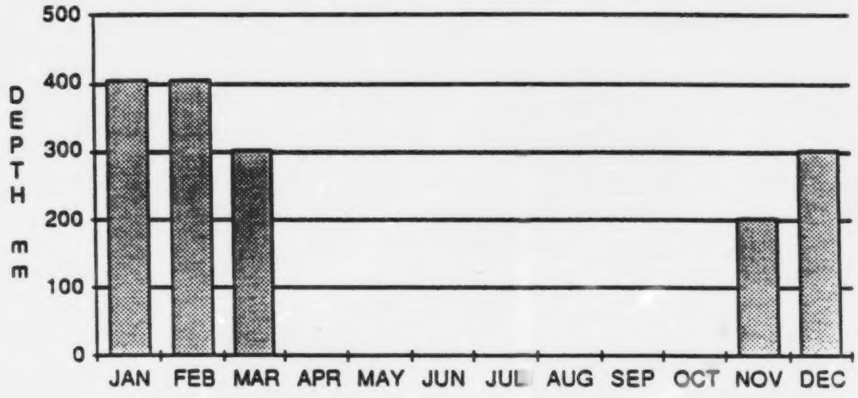
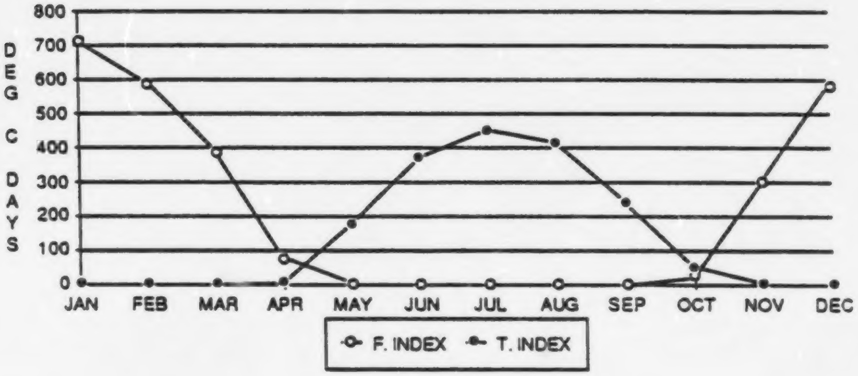


Figure 2.3-1a Cree Lake Meteorological Summary

MEDIAN SNOW DEPTH



FREEZING AND THAWING INDICES



POTENTIAL EVAPOTRANSPIRATION

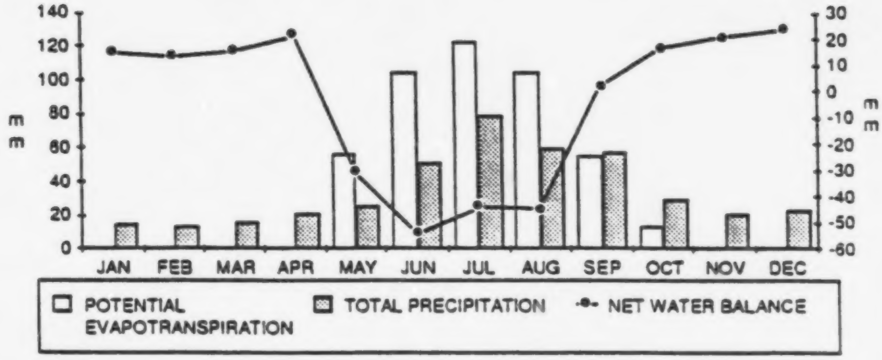


Figure 2.3-1b Cree Lake Meteorological Summary

2.3.3 SITE

A site plan is shown on Figure 2.3-2. The tailings are contained within earth dykes. The storage basin is 720 m square and the ultimate tailings thickness is 15 m. A zoned embankment and a bentonite modified liner, for a seepage barrier, is employed. A drainage blanket is provided under the tailings and below the embankment to direct seepage fluids to a intercepting structure. A bentonite-modified till liner underlies the drain. A typical cross section is shown on Figure 2.3-3.

A typical stratigraphic column within the tailings basin is shown on Figure 2.3-4. Granular till underlies the tailings to a depth of approximately 4 m. Sandstone of the Athabasca Formation underlies the till to a depth of 13 m and overlies Precambrian basement rock. Tailings are currently being deposited in the impoundment.

The piezometric surface is approximately 500 mm above the base of the impoundment. After decommissioning, the head is expected to drop to within the filter. As a result of the fine-grained nature of the tailings, the moisture content above the water table remains relatively high.

Materials properties are summarized in Table 2.3-2. The data was taken from Knight and Piesold (1985, 1986) reports. Considerable laboratory work has been done to characterize the tailings properties and the engineering characteristics of the till. Properties of the bedrock deposits are estimates.

TABLE 2.3-2
KEY LAKE TAILINGS SUMMARY

	TAILINGS	TILL	SANDSTONE	BASEMENT
Thickness (m)	4	4	17	rock
Moisture Content (%)	130	6	5*	5*
Dry Density (kg/m^3)	640	1900	2200*	2200*
Specific gravity	2.64	-	-	-
Gradation				
Gravel (%)	-	19	-	-
Sand (%)	30	76	-	-
Silt & Clay (%)	70	5	-	-
Relative Density (%)		70		
Permeability (m/s)				
Oedometer	10^{-8}	-	-	-
Permeameter	10^{-7}	-	-	-
In Situ	-	2.8×10^{-6}	3×10^{-6}	5.6×10^{-7}
Coefficient of Consolidation (m^2/yr)	50	-	-	-
Coefficient of Compression (m^2/kN)	0.0008	-	-	-
Mineralogy				
Quartz (%)	38	-	Predominantly quartz	Granitic gneiss
Carbonate (%)	2	-		
Clay (%)	23	-		
Gypsum (%)	26	-		
Other (%)	11	-		
Porewater TDS (mg/L)	4500	<50**	<50**	<500**

* Estimated

** Estimated from Conductivity

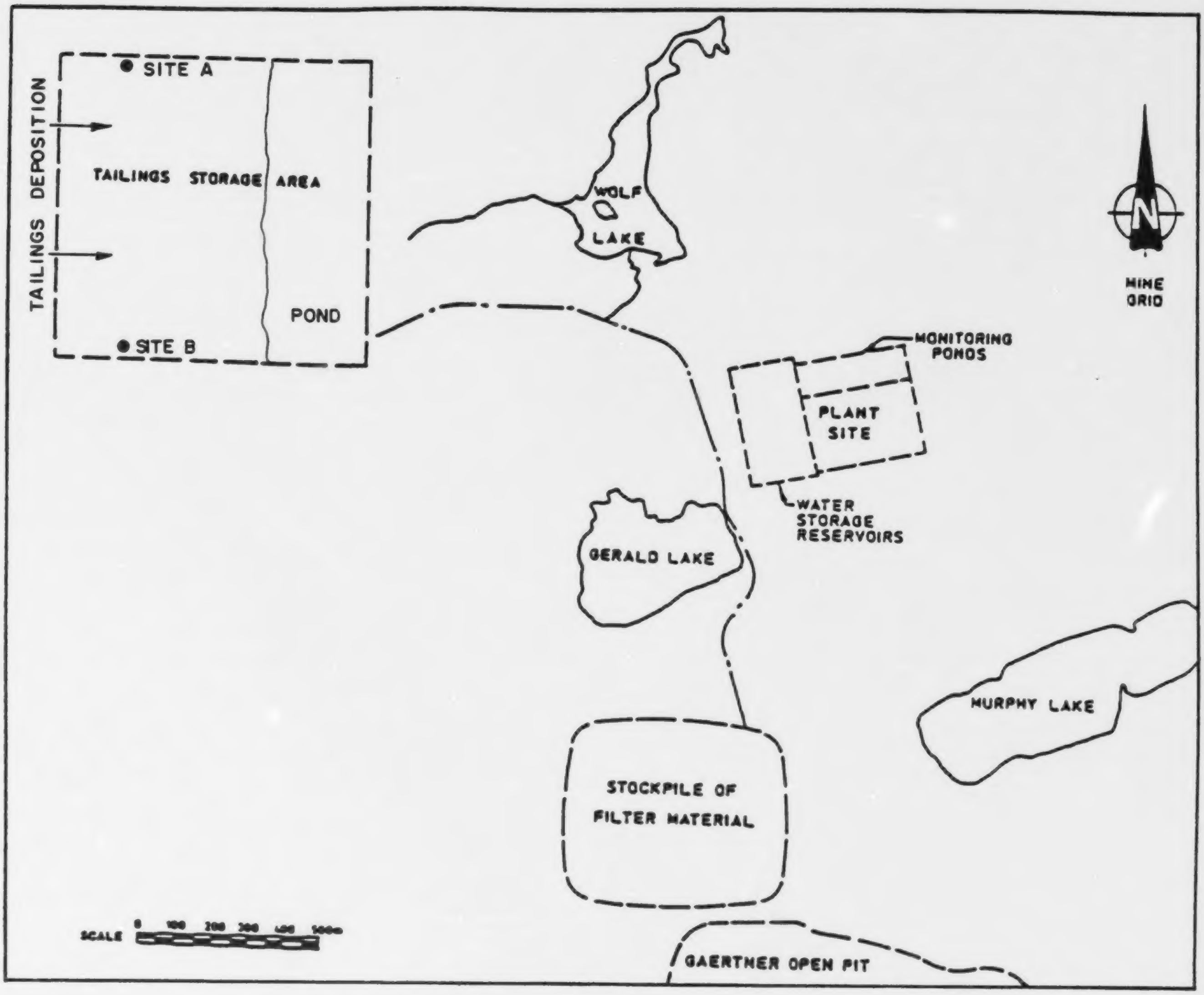
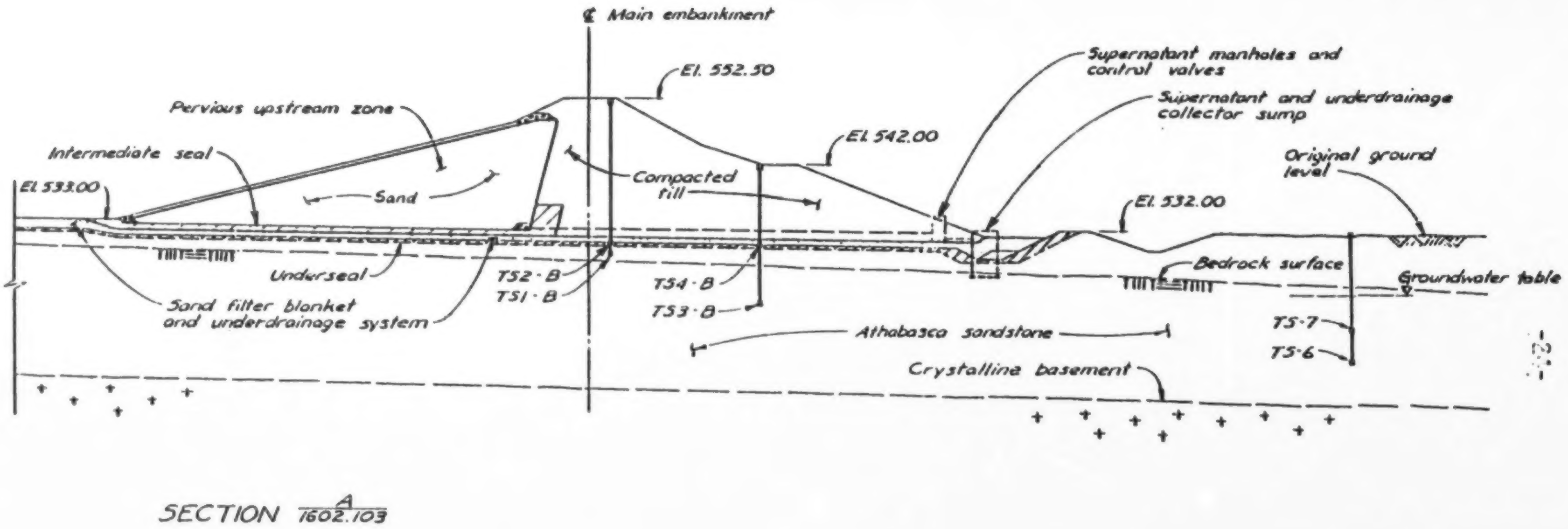

SITE A
TAILINGS DEPOSITION
TAILINGS STORAGE AREA
POND
SITE B
WOLF LAKE
MONITORING PONDS
PLANT SITE
WATER STORAGE RESERVOIRS
N
MINE GRID
GERALD LAKE
MURPHY LAKE
STOCKPILE OF FILTER MATERIAL
SCALE 0 100 200 300 400 500m
GAERTNER OPEN PIT

Figure 2.3-2 Layout - Key Lake


℄ Main embankment
El. 552.50
Pervious upstream zone
Intermediate seal
El. 533.00
Sand
Compacted fill
El. 542.00
Supernatant manholes and control valves
Supernatant and underdrainage collector sump
Original ground level
El. 532.00
Bedrock surface
Groundwater table
Underseal
Sand filter blanket and underdrainage system
TS2 · B
TS1 · B
TS4 · B
TS3 · B
Athabasca sandstone
TS-7
TS-6
Crystalline basement
SECTION $\frac{A}{1602.103}$

NOTE
All elevations are in metres.

Figure 2.3-3 Typical Embankment Section - Key Lake

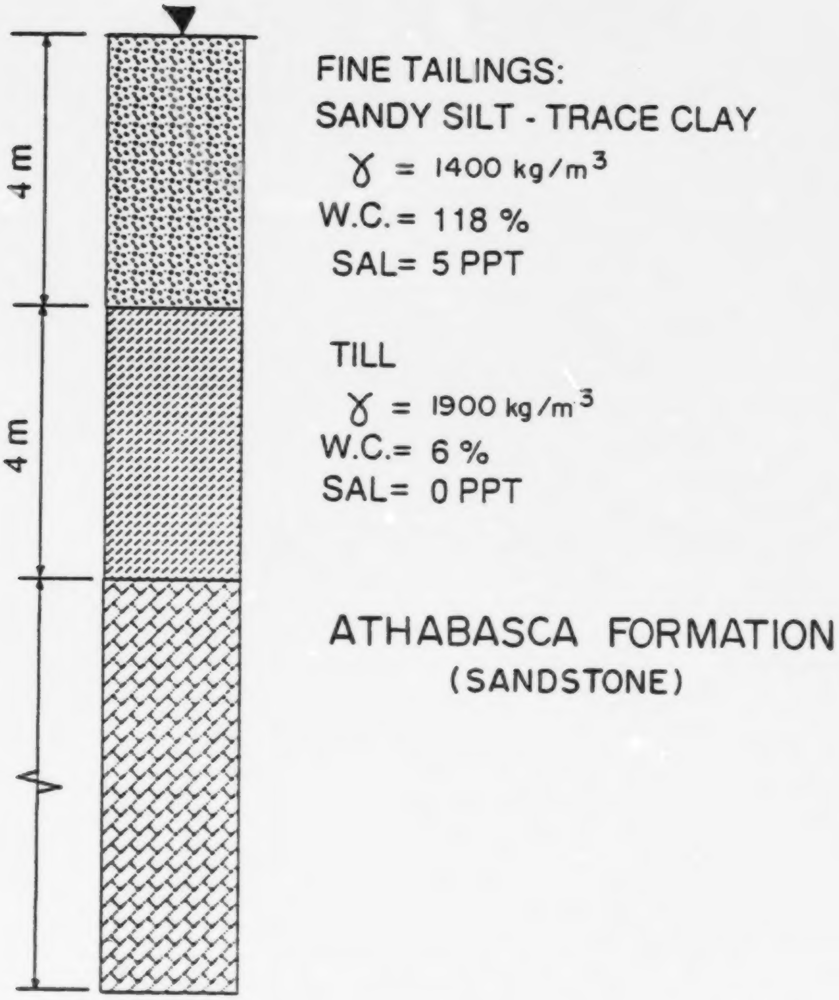

4 m
4 m
FINE TAILINGS:
SANDY SILT - TRACE CLAY
γ = 1400 kg/m³
W.C. = 118 %
SAL= 5 PPT
TILL
γ = 1900 kg/m³
W.C.= 6 %
SAL= 0 PPT
ATHABASCA FORMATION
(SANDSTONE)

Figure 2.3-4 Soil Profile Analyzed for Key Lake

The tailings are predominantly silt and clay sized particles with a high moisture content (130%) and low dry density (640 kg/m^3). There is a high gypsum content (26%) in the tailings.

The total dissolved solids in the pore water is moderately high (4500 mg/L) and quite low in the underlying till and sandstone (less than 50 mg/L measured before pond construction).

The drift is a dense, gravelly sand till. The bedrock sandstone and granitic gneiss basement rock are dense, low moisture content materials. They have a low to modest permeability derived from fracture porosity.

2.3.4 TAILINGS DEPOSITION

The tailings are deposited by the subaerial technique, (see the main volume of the manual). They are deposited from spigots on an exposed beach to promote drying during deposition. Underdrainage to a seepage collection sump is also provided. In summer, each fresh deposition of tailings is exposed to the air, enhancing drying and promoting desiccation of the tailings. In winter, the tailings are exposed to freezing temperatures. In areas of active deposition, the heat content of the tailings appears sufficient to limit frost penetration.

2.3.5 FROST OBSERVATIONS

The available ground frost observations consist of:

- Temperature measurements.
- Probing for frozen tailings.
- Observations of hummocks and segregated ice.
- Freeze/thaw tests.

2.3.5.1 Temperature Measurements

Two sites, Site A on north side, Site B on south side, were monitored in the 1984 program (Figure 2.3-2). Active deposition of warm tailings had occurred at site A during the summer; no tailings deposition had occurred during the winter. Tailings were covered with an unknown amount of snow. The maximum depth of frost was approximately 500 mm in mid-February. As a result of the snow cover and high initial ground temperature, this observation likely under estimates the average depth of frost.

Winter tailings deposition occurred at Site B. The frost penetrated to approximately 600 mm below the tailings surface in the fall, and 600 mm of tailings placed during the winter were frozen, for a total frost depth of 1.2 m. The temperature sensor at 600 mm depth recorded a temperature of 0°C from January to mid-March. By probing, it was determined that thawing at both sites was complete by June 1985.

The 1985 observations were taken only until October 1985. At Site A, approximately 100 mm of tailings had been deposited from March to October. The 0° isotherm had penetrated to at least 1,000 mm by October 28. At Site B, active tailings deposition was occurring. Approximately 1.3 m of tailings had been deposited from March to October. At the onset of winter, approximately 1 m of fresh tailings overlay the uppermost temperature sensor. No freezing temperatures were observed. The ground temperature at the base of the fresh tailings was approximately 10°C throughout the March to October period. This is substantially above the natural ground temperature and reflects the heat content of the deposited tailings.

In summary, 500 mm of frost was observed in high initial ground temperature and snow cover conditions. Under active winter deposition, 1.2 m of frost was observed. When tailings deposition is complete, the characteristic frost depth will likely be within this range (0.5 to 1.2 m).

2.3.5.2 Freeze-Thaw Tests

Knight and Piesold conducted laboratory freeze-thaw tests of the tailings. The purpose was to examine the effects of freeze-thaw on the drainage characteristics of the tailings. Tests consisted of placing 6 samples of tailings slurry at the discharge moisture content in plastic cylinders and subjecting them to a variety of freeze-thaw and settling cycles. The degree of drainage was determined by measuring the supernatant fluid after settling in a thawed condition. Freezing and settling increased the density by about 50% over unfrozen control tests for both one way and two way (bottom) drainage tests. Bottom drainage by itself increased the settled density by about 50%. A porous structure developed when the tailings were frozen. Where there was no underdrainage, this structure completely collapsed upon thaw. Where the sample was frozen after underdrainage, the porous structure that had formed during freezing remained intact after thaw.

Observations on tailings in the summer show a porous structure in some samples, likely the result of prior freezing.

2.3.5.3 Frost Probing

On July 11, 1985, probing at Site B to a depth of 3 m showed that no frost was present. This is consistent with the temperature measurements. In September 1985, buried ice was located at a depth of 600 mm near the southeast corner of a temporary embankment. It was not investigated further nor were the surface conditions at this site known.

2.3.5.4 Frost Features

In inactive areas, significant frost heave of the tailings surface occurs. Knight and Piesold (1986) shows significant hummocking of the tailings, see Photo 2.3-1. From 1 to 1.2 m of differential movement of the tailings surface occurred during the winter of 1984. The tailings had been exposed to the atmosphere and were adjacent to standing water. The probable cause of the hummocks is frost heave. They have a distinctive, deeply cracked surface, characteristic of "pingo" structures.

2.3.5.5 Other Frost Effects

Photo 2.3-2 from Knight and Piesold (1986) shows an excavated frozen tailings face. It is not known whether these tailings were frozen in-situ or frozen as the tailings were deposited. A varying ice content within a uniform tailings mass is apparent. The tailings have developed layers approximately 50 mm in thickness, each with a similar ice content. Some have no visible ice. One zone has approximately 75% visible excess ice. Another zone appears to have little visible ice with a 4 mm central ice lense. In other zones, a reticular ice structure with approximately 30% ice content is present. The exposed section is 330 mm in thickness with an average of approximately 20% visible excess ice.

2.4 RABBIT LAKE

2.4.1 GENERAL

The Rabbit Lake mine is located at 58°15′ N latitude and 103°40′ W longitude in northeastern Saskatchewan.

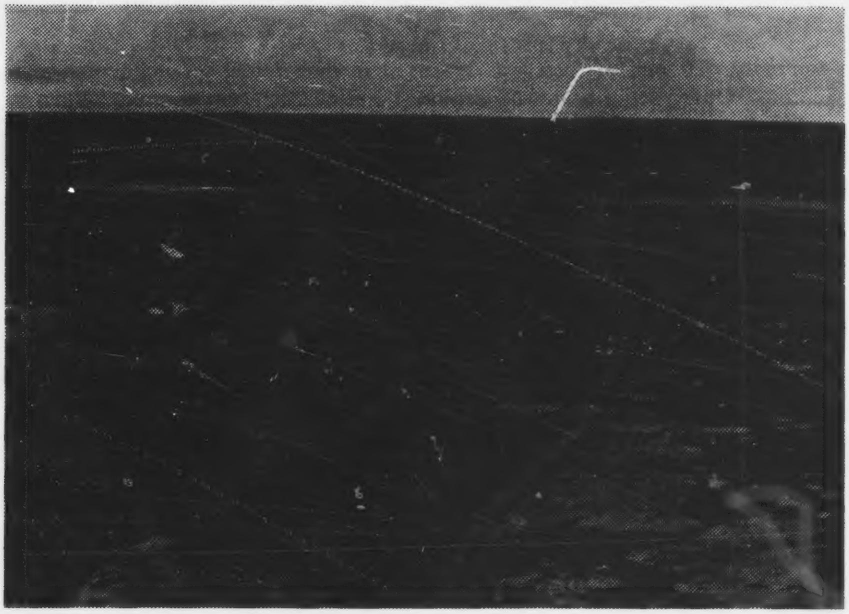


Photo 2.3-1 Thawed tailings surface at downstream end of Key Lake impoundment showing extensive hummocking about 1 m high. Previously this area had been covered with ice and tailings during the winter.

Photo 2.3-2

Partially thawed tailings material removed from Site A at Key Lake. Layering, ice lenses and variable structure are visible.

Photos from Knight and Piesold (1986)

2.4.2 CLIMATE

The Collins Bay meteorological station was established near the mine in 1972. The temperature, precipitation, wind and snow cover data for the period 1972 to 1980 are summarized in Table 2.4-1. Also presented are the calculated freezing/thawing indices and potential evapotranspiration calculated by the Thornthwaite method. The meteorological information is summarized on Figure 2.4-1a and b.

2.4.3 SITE

The site plan is shown on Figure 2.4-2. The setting and material characteristics were extracted from McClaren (1984) and Geocon (1987). The Rabbit Lake tailings impoundment was constructed in a naturally occurring lineament depression. Two earth filled dams were constructed at either end of the depression using a combination of centreline and downstream construction methods. The natural soils in the base of the depression consist of 0.3 to 1.0 m of muskeg overlying 5 to 6 m of granular glacial till. The muskeg was removed under the dam foundations and left within the tailings deposition area. The tailings thickness ranges from 20 to 23 m.

The tailings were discharged from the dams. The coarser sand sized tailings settle out near the dams and the finer textured tailings deposited in the central portion of the basin. Excess tailings water separates and runs to a decant pond.

2.4.4 MATERIAL PROPERTIES

The physical properties of the tailings and granular till are presented in Table 2.4-2. A typical soil profile is shown on Figure 2.4-3. The gradation of the tailings is more variable than Key Lake with up to 57% sand sized particles. The moisture content is relatively high (90%). The mineralogy is given in Geocon (1987), however, the high sulfate content of the tailings pore water (6350 mg/L) suggests a high gypsum content in the tailings.

TABLE 2.4-2
RABBIT LAKE MATERIALS SUMMARY

	TAILINGS	TILL
Depth (m)	0	20
Depth to water table (m)	0	
Moisture Content (%)	90	11*
Specific Gravity	2.6	2.7*
Dry Density (kg/m^3)	1540	2320
Gradation		
Gravel (%)	0	14-31
Sand (%)	50	27-61
Silt & Clay (%)	70	19-43
Permeability (m/s)	$2x10^{-5}$ to $1x10^{-7}$	-
Porewater TDS (mg/L)	8200	-

* estimated

2.4.5 GROUND FROST

Geocon (1987) observed frozen tailings in one test hole near the north dam of the impoundment area. This area had little winter cover and was likely an exposed surface during deposition. Other holes in the interior portion of the pond encountered no ice. The standard penetration resistance of the frozen

TABLE 2.4-1
RABBIT LAKE METEOROLOGICAL SUMMARY

STATION	COLLINS BAY	LATITUDE	58 deg 11 min N
PERIOD	1972-1980	LONGITUDE	103 deg 41 min W
		ELEVATION	490

DATA SECTION		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	ANNUAL
MEAN DAILY MAXIMUM TEMPERATURE	deg C	-22.5	-16.5	-10.3	1.7	9.7	16.3	19.4	17.8	10.1	2.8	-8.8	-18.3	0.1
MEAN DAILY MINIMUM TEMPERATURE	deg C	-30.2	-25.5	-21.4	-9.3	-1.6	4.8	9	7.9	2.5	-4.1	-15.8	-25.4	-9.1
MEAN DAILY TEMPERATURE	deg C	-26.2	-21.1	-15.7	-3.9	4.1	10.5	14.1	12.8	6.1	-0.9	-12.5	-22.1	-4.6
STANDARD DEVIATION, DAILY TEMP.	deg C	2.8	4.3	4	3.4	2.4	1.1	1.5	2.4	2.6	2.3	1.7	4.3	1
EXTREME MAXIMUM TEMPERATURE	deg C	3.3	4.4	10.6	27.2	26.5	28.3	31.3	27.8	22.2	19.9	11.5	1.7	31.3
EXTREME MINIMUM TEMPERATURE	deg C	-43.8	-42.5	-38.4	-30.9	-16.8	-3.9	1.4	-1.1	-9.7	-20.6	-35	-43.8	-48.9
MEAN RAINFALL	mm	0.2	0.1	0	3.8	31.9	53.2	85.9	66.1	55.5	11.2	0.5	0	308.4
MEAN SNOWFALL	mm water	19.6	21.7	27.7	32.8	7.2	4.3	0	1	8.7	30.2	54.8	38	348.6
MEAN TOTAL PRECIPITATION	mm	16.9	17.6	22.9	29.3	46.1	56.4	85.9	66.8	68.2	37.9	43.7	30.9	522.6
STD. DEVIATION, TOTAL PRECIPITATION	mm	7	9.1	9.1	16.1	33.1	29.9	31.3	21.7	28.8	30.4	12.5	9	92.6
MEAN WIND SPEED	km/hr	12.1	12.8	13.2	14.8	14.0	12.7	13.2	13.3	13.2	13.9	13.1	12.4	13.2
PREVAILING DIRECTION		W	S	S	S	E	E	W	W	S	S	S	W	S
MEDIAN DEPTH OF SNOW COVER	mm	196	217	277	328	72	43		1	87	302	548	380	
SOLAR RADIATION	W/sq. m	29.00	73.00	143.00	218.00	274.00	266.00	252.00	199.00	111.00	62.00	29.00	18.00	
DERIVED SECTION														
FREEZING INDEX	deg C days	752	632	447	131						59	368	642	3030
THAWING INDEX	deg C days					117	305	405	364	182	14			1386
		FREEZING		THAWING										
PERIOD	days	200		165										
STEP TEMPERATURE	days	-15.1		8.4										
POTENTIAL EVAPOTRANSPIRATION	mm	0	0	0	0	47	96	119	102	50	0	0	0	414
NET WATER BALANCE	mm	17	18	23	29	-1	-39	-34	-35	18	38	44	31	109

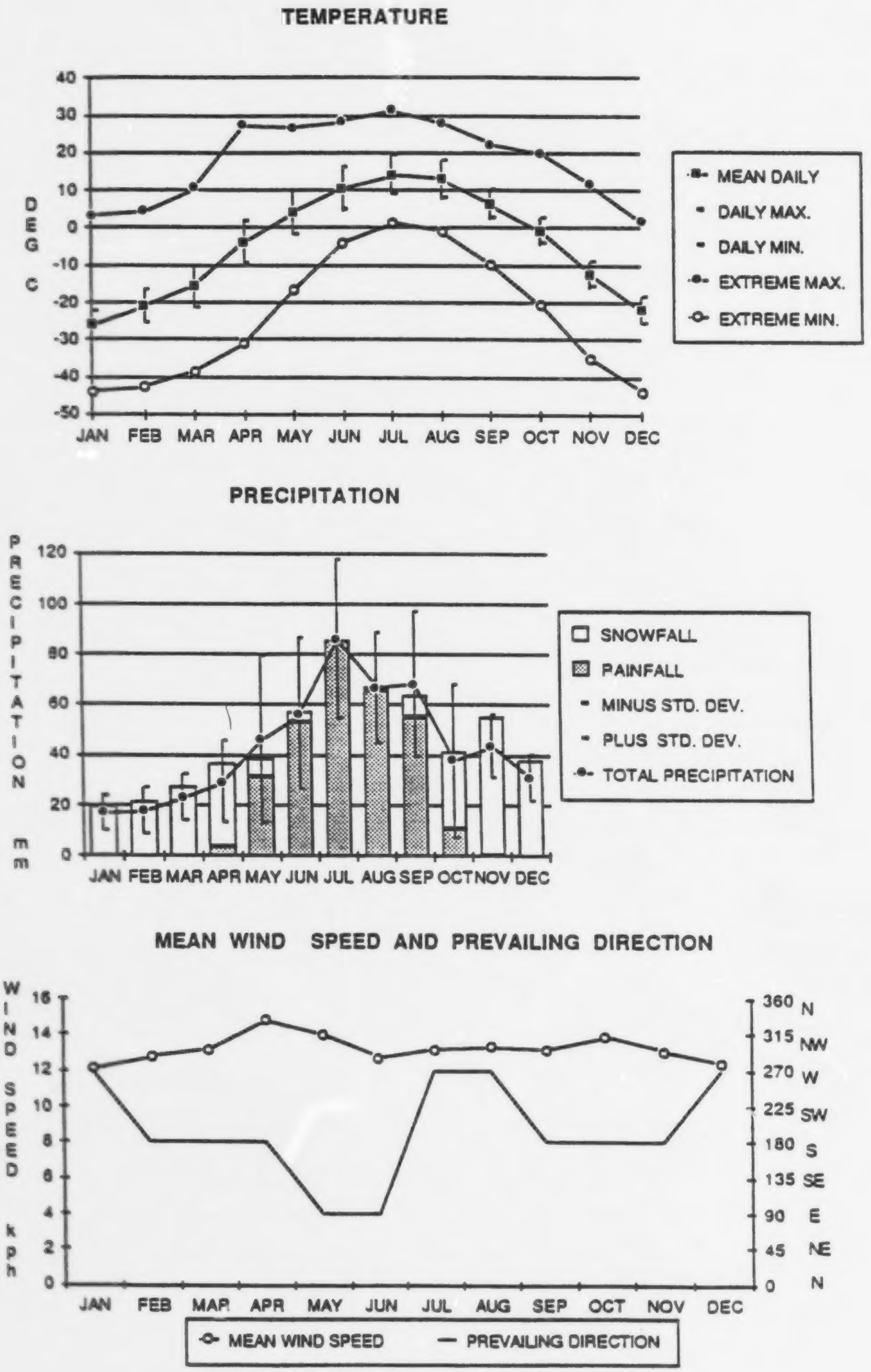
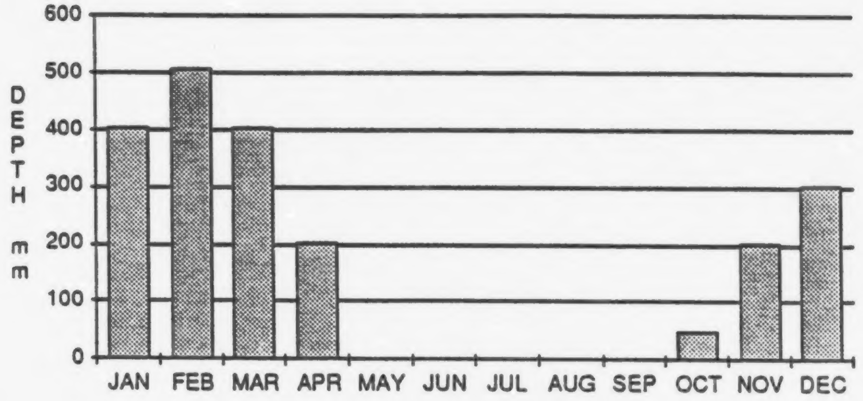
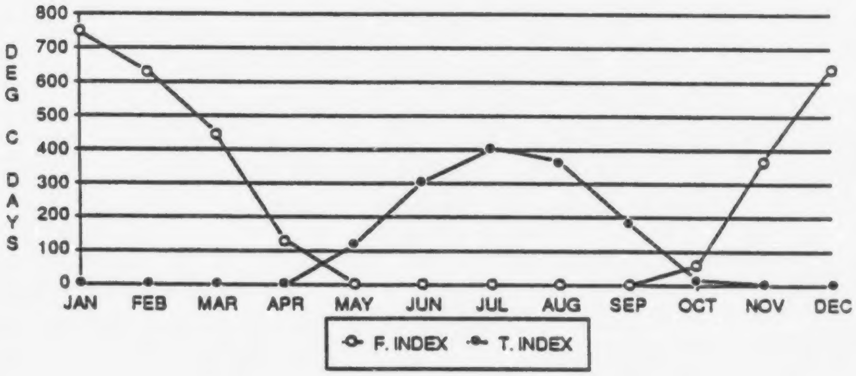


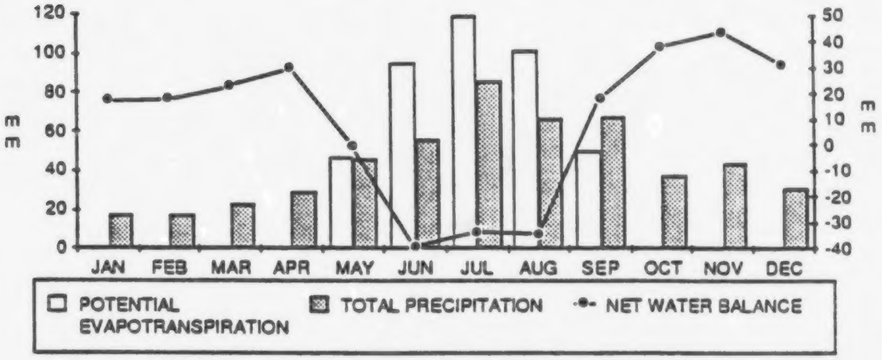
Figure 2.4-1a Collins Bay Meteorological Summary (Rabbit Lake)



MEDIAN SNOW DEPTH



FREEZING AND THAWING INDIC ES



POTENTIAL EVAPOTRANSPIRATION

Figure 2.4-1b Collins Bay Meteorological Summary (Rabbit Lake)

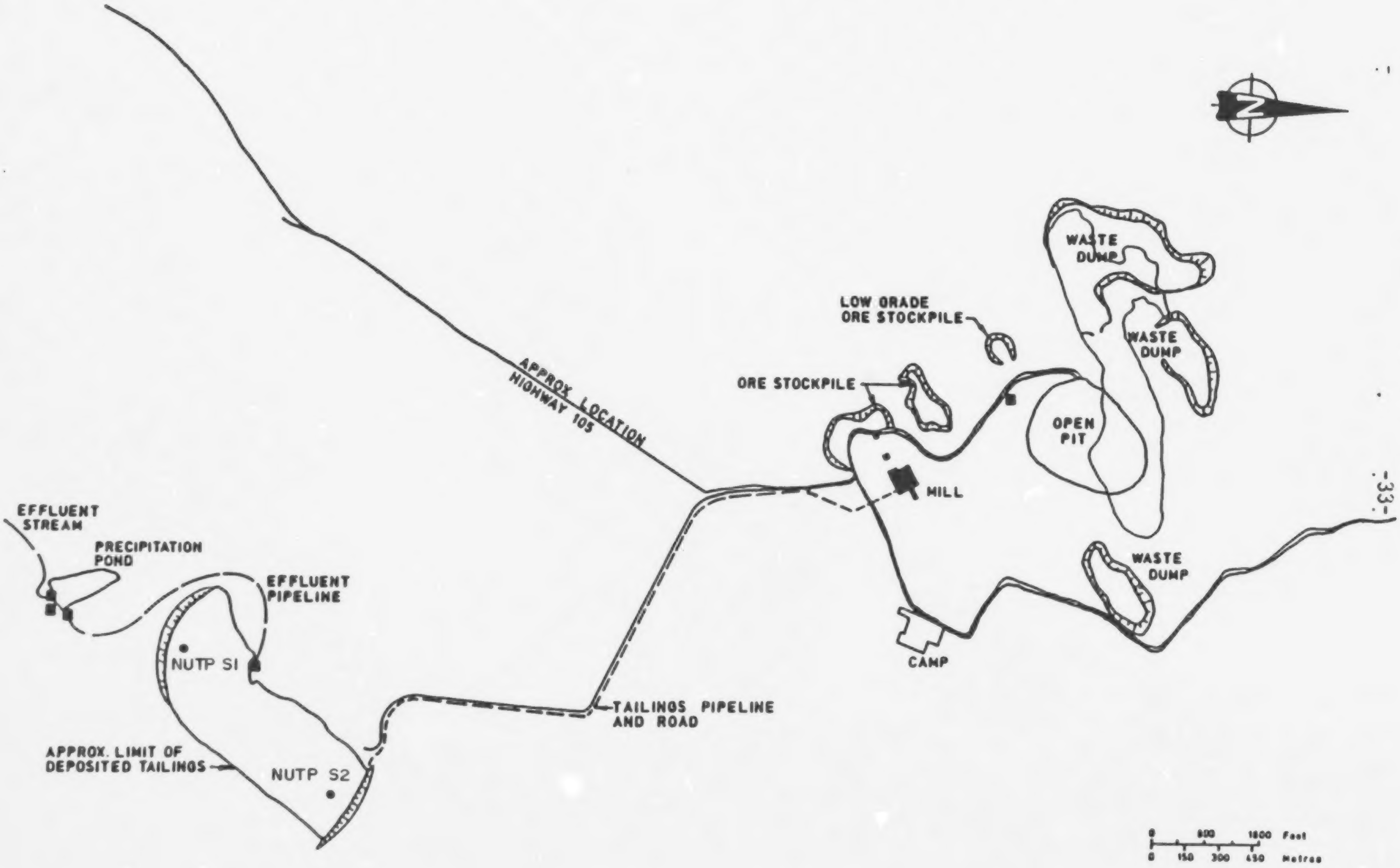

N
APPROX LOCATION
HIGHWAY 105
LOW GRADE
ORE STOCKPILE
ORE STOCKPILE
WASTE
DUMP
WASTE
DUMP
OPEN
PIT
MILL
WASTE
DUMP
CAMP
TAILINGS PIPELINE
AND ROAD
EFFLUENT
STREAM
PRECIPITATION
POND
EFFLUENT
PIPELINE
NUTP S1
NUTP S2
APPROX. LIMIT OF
DEPOSITED TAILINGS
0
600
1800
Feet
0
150
300
450
Metres

Figure 2.4-2 Layout - Rabbit Lake

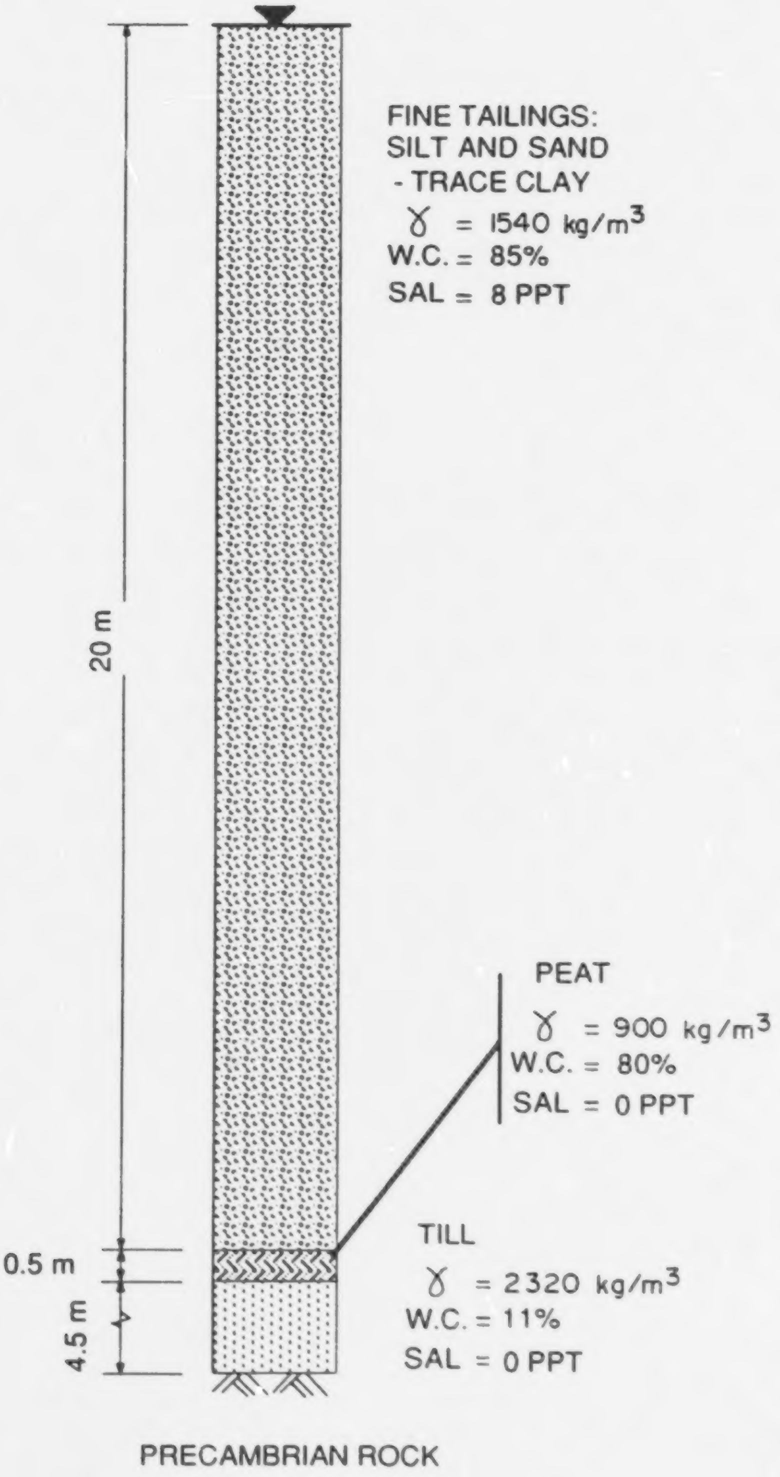

FINE TAILINGS:
SILT AND SAND
- TRACE CLAY
γ = 1540 kg/m^3
W.C. = 85%
SAL = 8 PPT
20 m
PEAT
γ = 900 kg/m^3
W.C. = 80%
SAL = 0 PPT
0.5 m
TILL
γ = 2320 kg/m^3
W.C. = 11%
SAL = 0 PPT
4.5 m
PRECAMBRIAN ROCK

Figure 2.4-3 Soil Profile Analyzed for Rabbit Lake Tailings

layers was up to 60 blows per 300 mm. No laboratory testing was carried out on samples from this test hole. It is unclear whether or not these tailings are coarser than the central tailings.

A second investigation program was undertaken by Geocon (1987). Several test holes were drilled; one of which, located near the north dam, encountered frozen tailings throughout its full depth. The frost is attributed by Geocon, to freezing during deposition. The frozen tailings were cored and moisture content testing performed. The moisture content profiles at Test Holes S1 and S2 were compared. Test Hole S1 is located near the south dam in a somewhat similar, although less complex, depositional environment. The gradation and moisture content data is compared in Table 2.4-3. The average gradation at Test Hole S2 is similar but somewhat finer grained than at Test Hole S1. On this basis, one would expect a slightly higher moisture content at Test Hole S1. This is not the case. The average moisture content at Test Hole S1 (frozen hole) is significantly higher. The higher moisture content is attributed to two factors. First, segregated, excess ice was observed in the frozen test hole. Secondly, the tailings would be frozen during, or within one year following, deposition and would not have had time to consolidate before freezing. The underconsolidated state would be "locked-in" by frost.

TABLE 2.4-3
COMPARISON OF FROZEN AND UNFROZEN TAILINGS AT RABBIT LAKE

SAMPLE	DEPTH	MOISTURE CONTENT	UNIT WEIGHT	GRAIN SIZE (% PASSING) SIEVE NO.				
	(m)	(%)	kN/m^3	20	40	60	100	200
TEST HOLE NUTP-S2 UNFROZEN TAILINGS								
1	3.05-3.81	75.7		100	94	83	20	4
2	4.57-5.33	86.9	16.1	100	100	100	97	92
3	6.1-6.86	68.9	15.1	100	99	95	87	64
4	7.62-8.38	88.5	14.8	100	100	100	96	90
5	9.14-9.91	33.8	17.2	100	87	50	25	14
6	10.67-11.43	87.6	14.4	100	100	100	98	96
7	12.19-12.95	63.0	16.6					
8	13.72-14.48	63.0	17.5	100	100	96	84	69
9	15.24-16	55.4	16.1	100	100	100	93	71
10	16.76-17.53	52.8	17.0	100	100	98	88	62
11	18.25-19.05	85.1	14.6	100	100	100	100	100
12	19.81-20.57	47.7	14.8	100	100	96	92	83
13	21.34-22.10	68.2	15.1	100	100	98	96	90
14	22.56-23.29	47.7	14.6	100	100	97	96	95
AVERAGE		66					84.8	71.6
TEST HOLE NUTP-S1 - FROZEN TAILINGS								
1A	4.01-4.33	207.6						
1B	4.33-4.44	50.9						
1C	4.94-4.51	81.2						
1D	4.51-4.95	103.6						
2A	5.84-6.74	86.5		100	100	97	91	71
2B	5.84-6.74			100	99	85	48	38
3	7.62-7.15	69.7		100	100	90	73	35
4	9.15-10.08	157.6		100	97	91	73	43
5	10.67-11.40	86.0						
6	12.09-13.01	102.6						
7	13.72-14.19	82.1		100	100	96	85	70
8A	14.98-16.31	67.6						
8B	14.98-16.58	60.4		100	93	84	74	60
9	16.76-16.81	79.0						
10	17.83-19.26	92.8		100	95	87	79	69
11	19.92-20.42	72.6		100	100	97	94	86
AVERAGE		93.3					77.1	59

CHAPTER 3.0
PROCESSES AND MECHANISMS

3.1 THE ISSUES

Decommissioning will likely entail construction of a cover or other surface treatment to minimize infiltration, promote surface runoff and likely stabilize the tailings against wind erosion. Typical tailings cover sections are illustrated on Figure 3.1-1.

The issues related to frost action in tailings are:

- Thaw of included ice. Tailings deposition on an exposed beach can result in frost aggradation. The thin tailing layers freeze and are subsequently covered with additional tailings. In the Rabbit Lake case, 15 m of frozen tailings were generated on the discharge beach. Will the frozen tailings thaw and how fast?; What is the long-term potential for settlement?; Will settlement continue after a reasonable decommissioning period?

- Permafrost aggradation. Are thermal conditions amenable to permafrost aggradation in decommissioned tailings impoundments? What conditions favour permafrost aggradation? Can reliance be placed on permafrost to immobilize pore fluids, and are methods available to enhance permafrost aggradation? Will aggradation result in significant heave and disrupt the surface drainage?

- Frost heave. Will seasonal frost heave disrupt surface drainage? Hummocks at Key Lake up to 1.2 m in height are attributable to frost heaving, see Section 2.3.5.4.

- Frost heave pumping effects. Will frost heaving increase pore fluid release by increasing upward pore fluid flow?

- Soil particle transport. This is a secondary issue. Can frost heaving transport particles of soil from depth to the surface?

- Hydraulic conductivity effects. What effect does freezing and thawing have upon tailings or cover fabric, and subsequently upon the permeability?

3.2 THERMAL PROCESSES

Ground thermal processes are central to all frost effects. When the ground surface is exposed to freezing temperatures, the pore water in the soil freezes. An idealized ground temperature profile is shown on Figure 3.2-1 for permafrost and seasonal frost conditions.

The temperature varies seasonally down to a depth of zero annual amplitude. Below this depth, which is typically 15 to 30 m below ground surface, the ground temperature profile is determined by the geothermal gradient. In permafrost terrain, the upper zone of soil freezes and thaws annually. This zone is the active layer and the base of the active layer is the permafrost table. In non-permafrost conditions, the upper zone is the zone of seasonal frost. Permafrost conditions are defined as the persistence of freezing soil temperatures for more than 2 years.

The magnitude of temperature fluctuations and the resulting depth of seasonal freezing and thawing is controlled by:

- Heat conduction within the soil.

- Heat exchange at the ground surface.

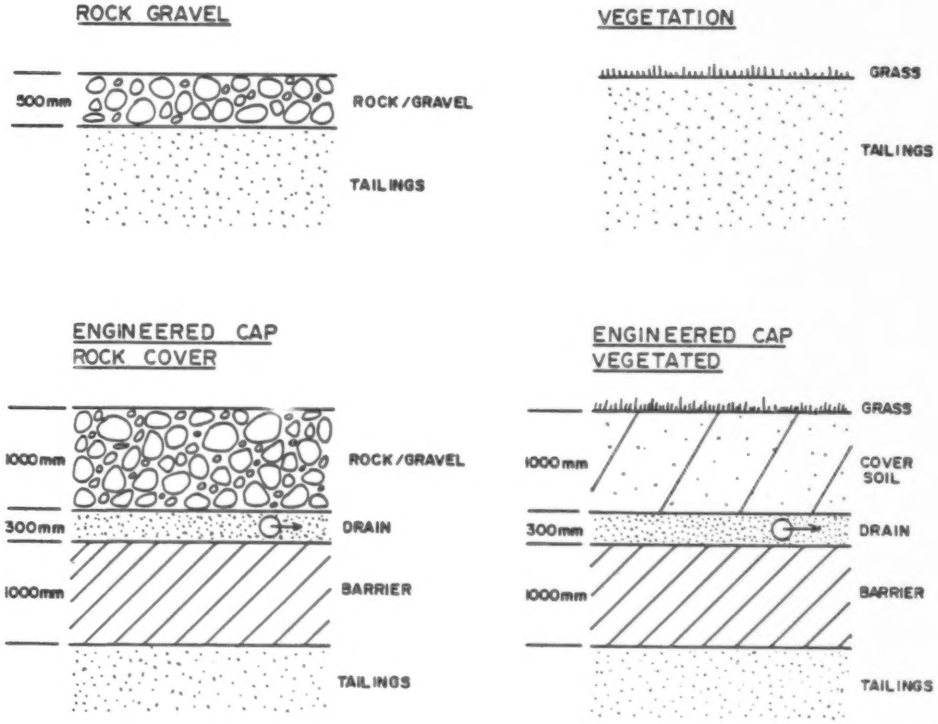

ROCK GRAVEL
500mm
ROCK/GRAVEL
TAILINGS
VEGETATION
GRASS
TAILINGS
ENGINEERED CAP
ROCK COVER
1000mm
ROCK/GRAVEL
300mm
DRAIN
1000mm
BARRIER
TAILINGS
ENGINEERED CAP
VEGETATED
GRASS
1000mm
COVER SOIL
300mm
DRAIN
1000mm
BARRIER
TAILINGS

Figure 3.1-1 Alternative Covers

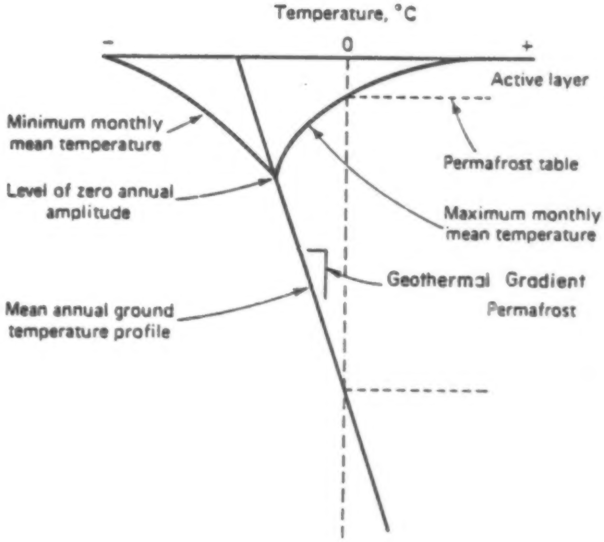

Temperature, °C
-
0
+
Active layer
Minimum monthly mean temperature
Permafrost table
Level of zero annual amplitude
Maximum monthly mean temperature
Geothermal Gradient
Mean annual ground temperature profile
Permafrost

Figure 3.2-1 Idealized Ground - Temperature Profile in Permafrost Terrain

Heat conduction in soils is well understood. Soil freezing is complicated by the latent heat of freezing of the soil moisture. The soil parameters required to characterize heat conduction are the frozen and unfrozen thermal conductivity and specific heat of the soils as well as the latent heat of freezing. Each of these parameters depends primarily upon the dry density and moisture content of the soil.

Heat exchange at the ground surface is more complex. In simple form, the heat exchange (Andersland and Anderson 1978) is given by:

$$R + LE + P + B = 0$$

where R = net radiation

LE = heat evolved in evaporation and evapotranspiration

P = heat evolved in convection (turbulent heat exchange)

B = ground heat flux

The heat balance is illustrated on Figure 3.2-2. The energy balance is dependent upon meteorological conditions as well as vegetation, snow cover, and other ground surface characteristics.

Computer thermal models can handle the complexity of ground surface heat exchange explicitly while simplified thermal models rely upon correlations between air temperature and ground surface heat exchange. Both approaches are discussed in more detail in Chapter 4.0.

In summary, the ground thermal regime is controlled by heat exchange at the ground surface and heat conduction with depth. Heat exchange at the ground surface is affected by site specific parameters such as vegetation and local evaporation as well as general climatic conditions. Saskatchewan mines are located in areas of discontinuous permafrost where the balance between permafrost and non-permafrost conditions is quite sensitive. As a result, local ground surface conditions exert a strong influence upon whether permafrost or non-permafrost conditions are favoured. The soil thermal properties and resulting heat conduction in the soil is strongly influenced by the soil moisture content.

3.3 FROST HEAVE PROCESSES

Frost heave occurs when water moves towards the freezing front during soil freezing. Ice, considerably in excess of the normal pore volume of the soil, accumulates at the freezing front.

When pore water freezes in small pore spaces, a suction pressure develops in the water space. The physics of soil freezing and the suction pressure development are discussed in detail in Chapter 6.0. The suction pressure causes flow towards the freezing front where the water accumulates and freezes. The amount of water flow depends upon the soil pore size characteristics, soil permeability, the rate of freezing and the overburden pressure at the freezing front.

Three components are necessary for frost heave to occur:

- Freezing temperatures.
- Water available in excess of saturation volumes.
- Frost susceptible soils.

The silty tailings are frost susceptible. The water table is near surface for both the Gunnar and Rabbit Lake tailings deposits. The Key Lake tailings are underdrained and, sometime after abandonment,

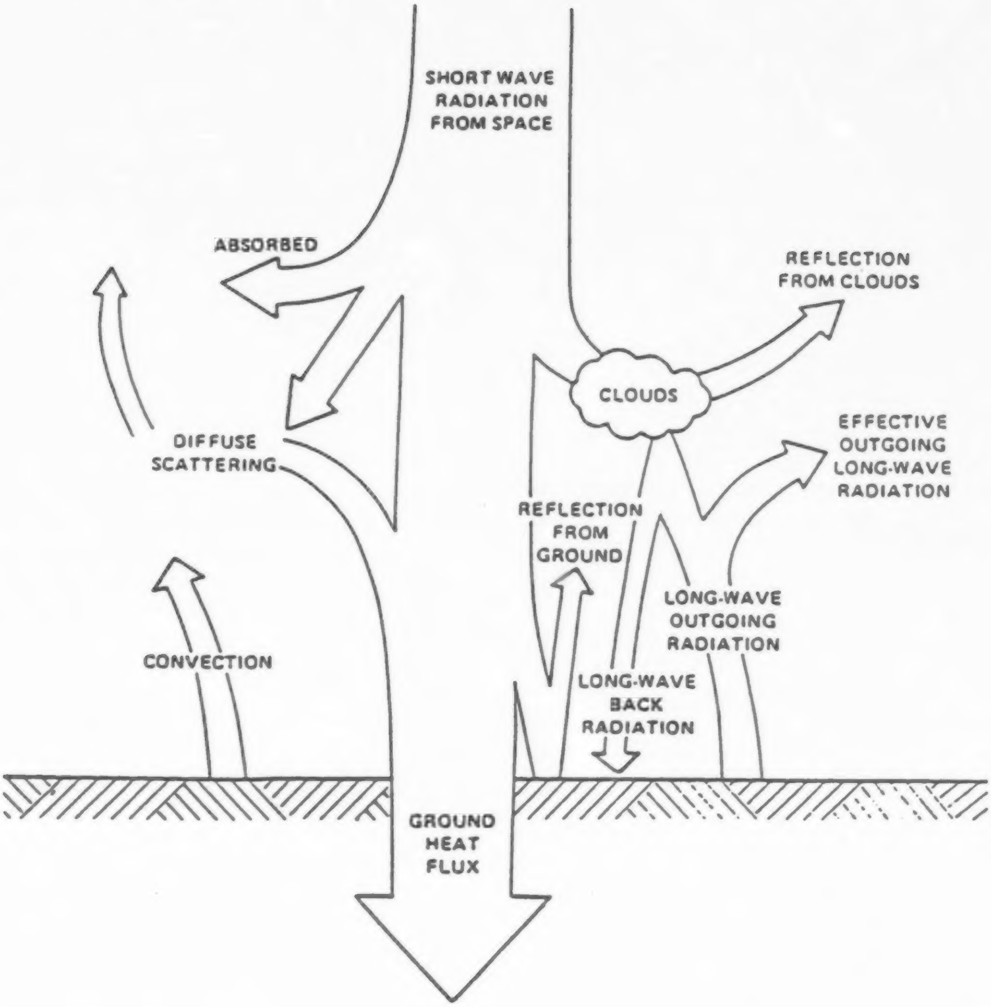

SHORT WAVE RADIATION FROM SPACE
ABSORBED
REFLECTION FROM CLOUDS
CLOUDS
DIFFUSE SCATTERING
EFFECTIVE OUTGOING LONG-WAVE RADIATION
REFLECTION FROM GROUND
LONG-WAVE OUTGOING RADIATION
CONVECTION
LONG-WAVE BACK RADIATION
GROUND HEAT FLUX

Figure 3.2-2 Heat Transfer at the Ground on a Sunny Day (from Kent and Hwang, 1979)

they may become sufficiently drained so that frost heave will not occur. Currently, there is sufficient moisture available for frost heave from locally ponded water and moisture within the tailings.

The amount of heave can be estimated (see Chapter 6.0); however, predictive technology is not fully developed. Up to 50% heave is not uncommon under favorable conditions.

Under conditions of seasonal freezing, the frost heave process may "pump" fluid to the surface. Ice is concentrated within the soil by the frost heave process. Subsequent thawing occurs from the surface down and liberates the frozen water. If the water released is in excess of the normal pore volume of the soil, it will flow toward the surface since downward flow is blocked by the underlying frost. The release is governed by the principles of thaw consolidation.

In some soils, the reverse process occurs. Pore water is expelled from the freezing front as some of the water expands in forming ice. If confined, the expelled water can surface in weak spots in the frozen crust and accumulate in mounds. The "pingos" in the Arctic are attributed to this process.

3.4 THAW CONSOLIDATION

When a soil is frozen and thawed under closed system conditions, very little heave or settlement, corresponding only to the volume expansion of phase change, occurs. When a soil freezes under open conditions, considerable ice accumulation, as discussed above, may occur. When the soil is subsequently thawed, the water is liberated and settlement of the soil occurs. Total settlement resulting from thaw is therefore composed of three components:

- Phase change.
- Settlement under self-weight.
- Settlement under applied load (i.e. covers).

The total settlement can be determined from thaw consolidation tests where frozen soil is allowed to thaw in an oedometer. A typical settlement versus pressure relationship is presented on Figure 3.4-1.

The amount of settlement upon thaw is characterized by the thaw strain parameter, A_o, which is the strain upon thaw under a nominal surcharge load.

Typically, soils with a high ice content and low bulk density have a greater thaw strain parameter. A correlation between bulk density and thaw strain is presented on Figure 3.4-2. Rough estimates of thaw strain can be made knowing the bulk density. Specific testing must be carried out for more reliable estimates.

The second aspect of thaw consolidation is the rate of settlement or the corresponding rate of fluid release. The rate of settlement is controlled by the rate of thaw and the rate at which fluid can escape from the thawing front. For conditions where the rate of thaw and water liberation is fast with respect to the rate of dissipation, excess pore water pressures will develop at the thawing front and the drainage properties of the soil will control the rate of settlement. Where the drainage capacity of the soil is large with respect to the rate of thaw, thawing will govern the rate of settlement.

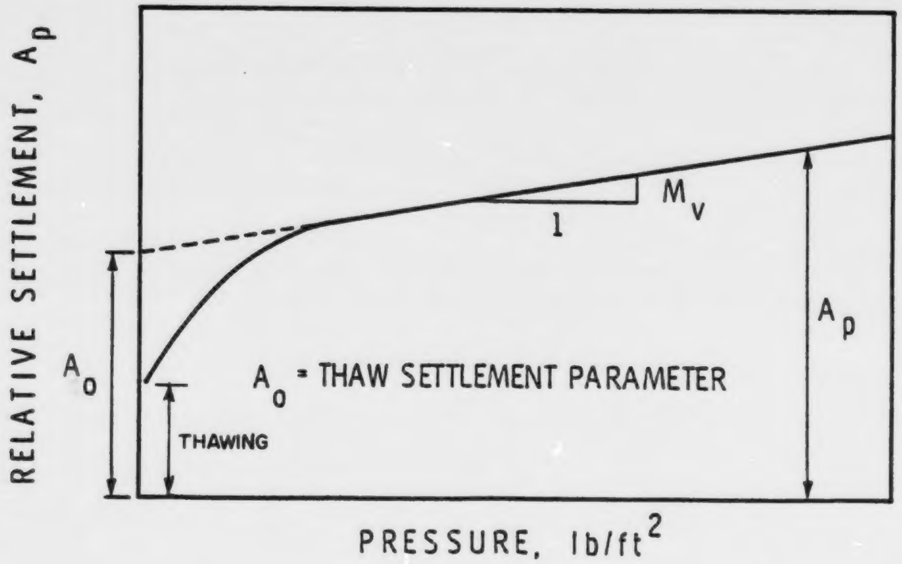

RELATIVE SETTLEMENT, A_p
M_v
1
A_p
A_0
A_0 = THAW SETTLEMENT PARAMETER
THAWING
PRESSURE, lb/ft^2

Figure 3.4-1 Generalized Thaw Settlement Curve

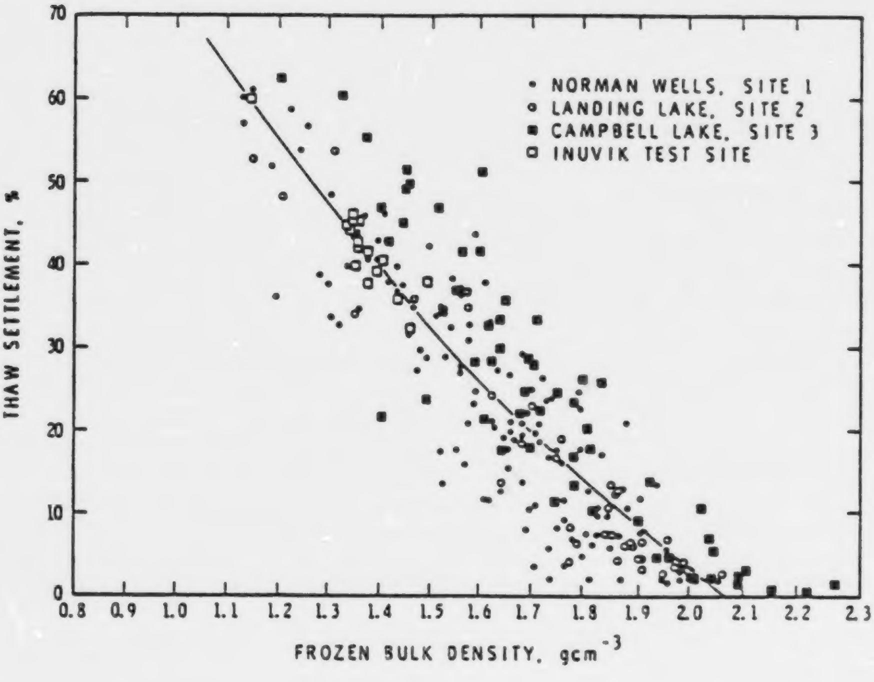


Figure 3.4-2 Thaw Settlement Vs. Frozen Bulk Density

The relative rate of thawing and drainage is expressed by the dimensionless thaw-consolidation ratio:

$$R = \frac{\alpha}{2c_v^{0.5}}$$

where R = thaw-consolidation ratio

α = thawing parameter (Section 4.2)

c_v = coefficient of consolidation of the thawed soil.

Figure 3.4-3 illustrates the average degree of consolidation of the thawed soil as a function of R. For low values of R (below 0.2), the soil is almost completely consolidated during thaw (i.e. the rate of thaw governs). However, when R is greater than 5 there is essentially no consolidation during the thawing time (drainage governs).

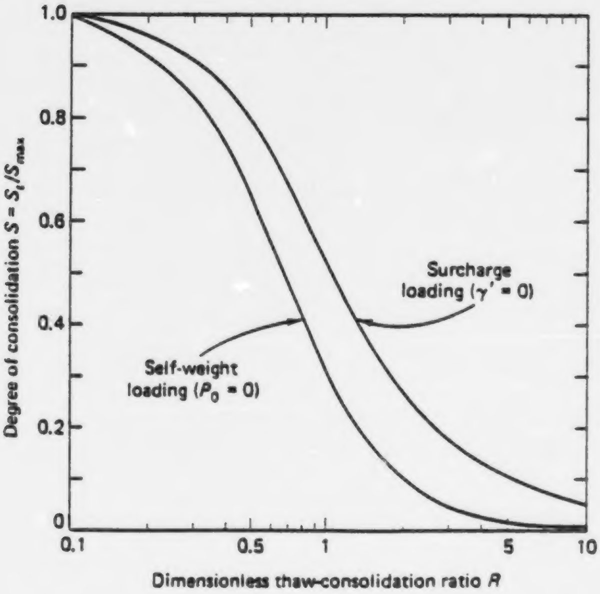


Figure 3.4-3 Variation of S with R

CHAPTER 4.0
GROUND THERMAL REGIME

4.1 GENERAL

The ground thermal temperature processes have been discussed in general terms in Section 3.2. In this section the thermal process is further illustrated with a description of a simple thermal model which predicts the depth of freezing or thawing.

The EBA geothermal model is described along with the input data requirements. Thermal analysis of each of the sites are presented and the significance of the results are discussed.

4.2 ILLUSTRATIVE THERMAL MODEL

The simple one-dimensional freezing and thawing model is presented to illustrate the thermal processes. The modelling of the ground thermal regime was carried out with a more sophisticated computer model.

The transient freezing process was first solved by Neumann and Stefan in the late 19th century. It is presented by Andersland and Anderson (1978) and Nixon and McRoberts (1973), and is extracted herein. A definition sketch for the Neumann problem is shown on Figure 4.2-1 for a thawing problem. When a mass of homogeneous, frozen soil is subjected to a thawing surface temperature, the thaw front will advance into the soil. When the temperature increases in a step-wise fashion from the initial ground temperature to the step temperature, a mathematical solution to the rate of thawing is available as follows:

$$\chi = \alpha\,(t)^{0.5}$$

where χ = depth of thawing or freezing

α = thaw constant

t = time

The constant alpha (α) is a function of several variables:

$$\alpha = f\,(k_u, k_f, c_u, c_f, T_g, T_s, L)$$

where k_u, k_f = unfrozen and frozen soil thermal conductivity (W/mK)

c_u, c_f = unfrozen and frozen volumetric specific heat (J/m^{3}K)

T_g = initial ground temperature (°C)

T_s = step temperature (°C)

L = volumetric latent heat (J/m^3)

The thaw constant α can be expressed in terms of three dimensionless variables:

$$\frac{\alpha}{2\kappa_u^{\,0.5}} = f\left\{\mathrm{Ste},\left[-\frac{T_g}{T_s}\frac{k_f}{k_u}\left(\frac{\kappa_u}{\kappa_f}\right)^{0.5}\right]\frac{\kappa_u}{\kappa_f}^{0.5}\right\}$$

where Ste is the Stefan number, defined as the ratio of sensible heat to latent heat

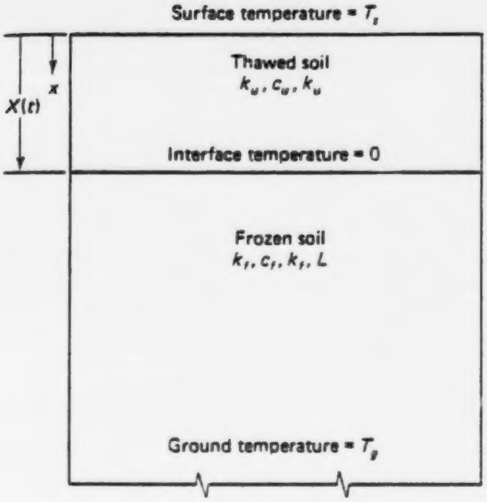

Surface temperature = T_s
Thawed soil
k_u, c_u, κ_u
x
$X(t)$
Interface temperature = 0
Frozen soil
k_f, c_f, κ_f, L
Ground temperature = T_g

Figure 4.2-1 The Neumann Problem (after Nixon and McRoberts, 1973)

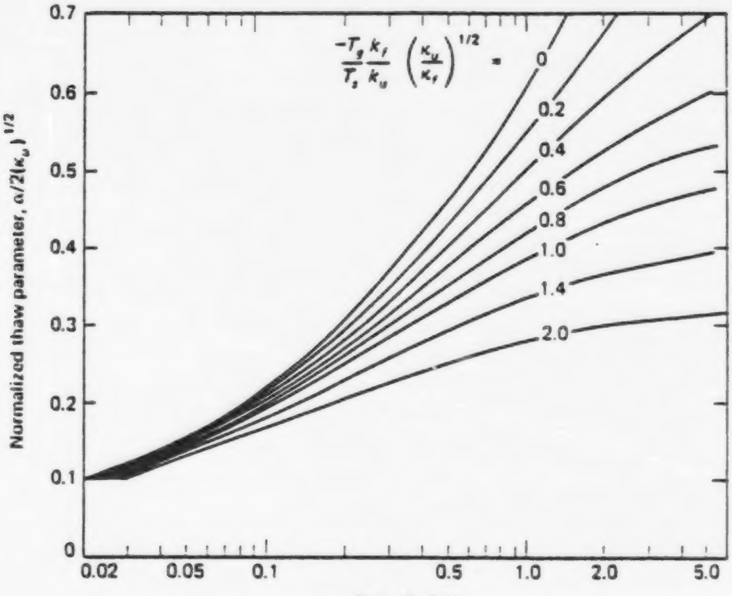


Figure 4.2-2 Graphical Solution of the Neumann Equation (after Nixon and McRoberts, 1973)

$$Ste = \frac{c_u T_s}{L}$$

where κ_u, κ_f = unfrozen and frozen soil thermal diffusivity $= \frac{k}{c}$ (m^2/s)

The thaw constant α is insensitive to $(\kappa_u/\kappa_f)^{0.5}$, therefore only 2 significant variables remain. The normalized thaw parameters are illustrated graphically in terms of those significant variables on Figure 4.2-2. For a case where the initial ground temperature T_g is close to the 0°C, the specific heat in the frozen zone can be neglected and,

$$\frac{\alpha}{2\kappa_u^{0.5}} = \frac{Ste^{0.5}}{2}\left(1 - \frac{Ste}{8}\right)$$

The rate of thaw is strongly dependent upon the components of the Stefan number (c_u, T_s, L) and less dependent upon the properties of the frozen zone at depth (especially if the initial ground temperature is close to zero).

4.2.1 HEAT EXCHANGE AT THE GROUND SURFACE

The heat exchange at the ground surface was discussed qualitatively in Chapter 3. In the simple solution, presented previously, the heat exchange at the ground surface is lumped into a single, equivalent ground surface temperature, which is empirically related to the air temperature.

Seasonal averages of the air temperature are used. The air freezing index is the number of degree-days where the temperature is above freezing. It can be obtained by integrating a plot of mean monthly air temperatures. The average temperature over the thawing period is the equivalent air step temperature.

The effect of different surface conditions is handled empirically by multiplying the air thawing index by an "n" value. Examples of "n" values are shown in Table 4.2-1. The "n" values account for different surface reflectivity, evapotranspiration exposure, etc. For example, the "n" values for both freezing and thawing in a spruce forest are much less than those in an exposed barren condition. This reflects the shading, reflectivity and snow cover and insulating properties of the vegetative cover. No "n" values have been expressly developed for mine tailings.

4.3 DESCRIPTION OF A GEOTHERMAL MODEL

In cold regions, ground thermal conditions have a strong influence on the behaviour of soils. Changes in ground temperatures can produce freezing and thawing, with corresponding changes in mechanical properties of the soils. Phase change effects may also include significant ground heave or settlement. Freezing of initially unfrozen soil occurs as the freezing point isotherm, or frost front, penetrates the ground in response to heat loss to the environment. The rate at which this occurs is governed by the soil's thermal properties, the magnitude of change in boundary conditions and the depth at which freezing is occurring. Changes in moisture content and phase composition occurring during initial freezing or thawing affect subsequent heat transfer and thermal processes. The response to a change in boundary conditions is initially transient, with resulting ground cooling and permafrost aggradation, or overall warming and thawing. Once the soil reaches thermal equilibrium with the environment, steady state conditions will prevail, with seasonal freezing and thawing.

TABLE 4.2-1

VALUES OF "n"-FACTORS FOR DIFFERENT SURFACES
(After Lunardini 1978)

SURFACE TYPE	FREEZING-n_f	THAWING-n_t
Spruce trees, brush, moss over peat - soil surface	0.29 (under snow)	0.37
As above with trees cleared - soil surface	0.25 (under snow)	0.73
Turf	0.5 (under snow)	1.0
Snow	1.0	-
Gravel	0.6 - 1.0	1.3 - 2
(probable range for northern conditions)	(0.9 - 0.95)	
Asphalt pavement	0.29 - 1.0 or greater	1.4 - 2.3
(probable range for northern conditions)	(0.9 - 0.95)	
Concrete pavement	0.25 - 0.95	1.3 - 2.1
(probable range for northern conditions)	(0.7 - 0.9)	

Ground temperatures and rates of heat flow may in principle be estimated based on boundary conditions and thermal properties. However a number of factors complicate the process, including the nonhomogeneity of the ground, the dependence of thermal properties on ground temperature and phase composition, the transient nature of the thermal regime and the occurrence of moving boundaries. A major factor is the effect of moisture content and phase composition on latent heat and thermal conductivity.

The actual flow and transfer of heat in a soil medium involves a number of complex phenomena. Mechanisms include conduction, evapotranspiration, condensation, moisture migration, convection in the pore air and/or porewater, and radiation through voids. In the early 1970's it was recognized that, because of the gradual heat exchange that occurs for most geotechnical problems, many configurations could be simulated using a conduction model (Hwang et al, 1972 and Hwang 1976). In this model mechanisms that are not conductive are simulated by equivalent conductivity tensors. With these assumptions, the governing principle becomes the well-known Fourier's law of heat conduction.

The EBA finite-element model, GEOTHERM, used for the analyses presented herein is based on the model developed by Hwang (1976). The model calculates transient heat conduction in soil of variable composition, accounts for latent heat of fusion within the soil and heat exchange at the ground surface, and has a moving boundary option to account for settlement or heave. The ground surface heat exchange is computed from meteorological data including air temperature, solar radiation, greenhouse factor, wind velocity, snow depth and evapotranspiration. The program is completely general with respect to material properties and boundary conditions. Details regarding the mathematical development of the model are described by Hwang (1976). The model accuracy has been verified with closed-form analytical solutions and field observations.

4.4 DATA REQUIREMENTS

4.4.1 GEOTHERMAL PROPERTIES

The principal material thermal properties required for the analysis are latent heat, specific heat and thermal conductivity. These can, of course, be measured directly, but are often estimated based on physical properties of the soil such as moisture content, grain size distribution and pore water salinity.

4.4.1.1 Latent Heat

The latent heat of fusion of the porewater within a soil is considered as a heat source in the conduction code. The latent heat of soil is computed by multiplying the latent heat of fusion of water by the volume of water that must change phase in order to freeze or thaw the soil. Not all of the moisture changes phase at a unique temperature; phase change and, hence, latent heat exchange occurs over a subfreezing temperature range. The amount of water that changes phase at any particular soil temperature is equivalent to the total moisture content minus the moisture content that remains unfrozen. The relationship between unfrozen moisture content and temperature is input to the GEOTHERM program for each soil unit in order to define latent heat.

The relationship between unfrozen moisture content and temperature for frozen soils depends on particle size distribution, particle shape (surface area), mineralogy and salinity. The unfrozen moisture within frozen saline soils is the sum of the moisture adsorbed by soil minerals and the unfrozen moisture within the brine pockets of the pore ice. Development of the unfrozen water content curve combines procedures of McGaw and Tice (1976) and Ono (1966).

Typical unfrozen water content curves for the fine-grained tailings are shown on Figure 4.4-1. The shape of the curves is dictated mainly by soil texture, whereas the position or starting point is determined by the total water content and the freezing point depression.

4.4.1.2 Specific Heat

The specific heat of frozen soils is computed by considering the specific heat of three constituents: soil grains, frozen moisture as pure ice and unfrozen moisture. The specific heat of frozen soil varies with temperature below the freezing point, due to the variation of unfrozen moisture content with temperature, as described above. The unfrozen moisture content is input into GEOTHERM together with unit specific heat values for the three constituents.

4.4.1.3 Thermal Conductivity

The thermal conductivity of frozen and unfrozen soil is normally estimated from experimental correlations developed by Kersten (1949). Kersten's correlations express soil thermal conductivity in terms of dry density and water content for both coarse-grained and fine-grained soils. Recently, Farouki (1981) presented a detailed evaluation of several available methods to estimate thermal conductivity of soils. He concluded that Kersten's method significantly underpredicts the thermal conductivity of unfrozen soils with a high quartz content. The method also overpredicts thermal conductivity for soils with a low quartz content.

Farouki (1981) suggested the use of Johansen's (1975) method to estimate the thermal conductivity particularly for unfrozen, coarse-grained soils having a high quartz content. The Johansen method, adopted for this analysis, considers the quartz content and unfrozen water content in addition to soil dry density and degree of saturation. With the exception of quartz, other soil minerals have a relatively constant thermal conductivity.

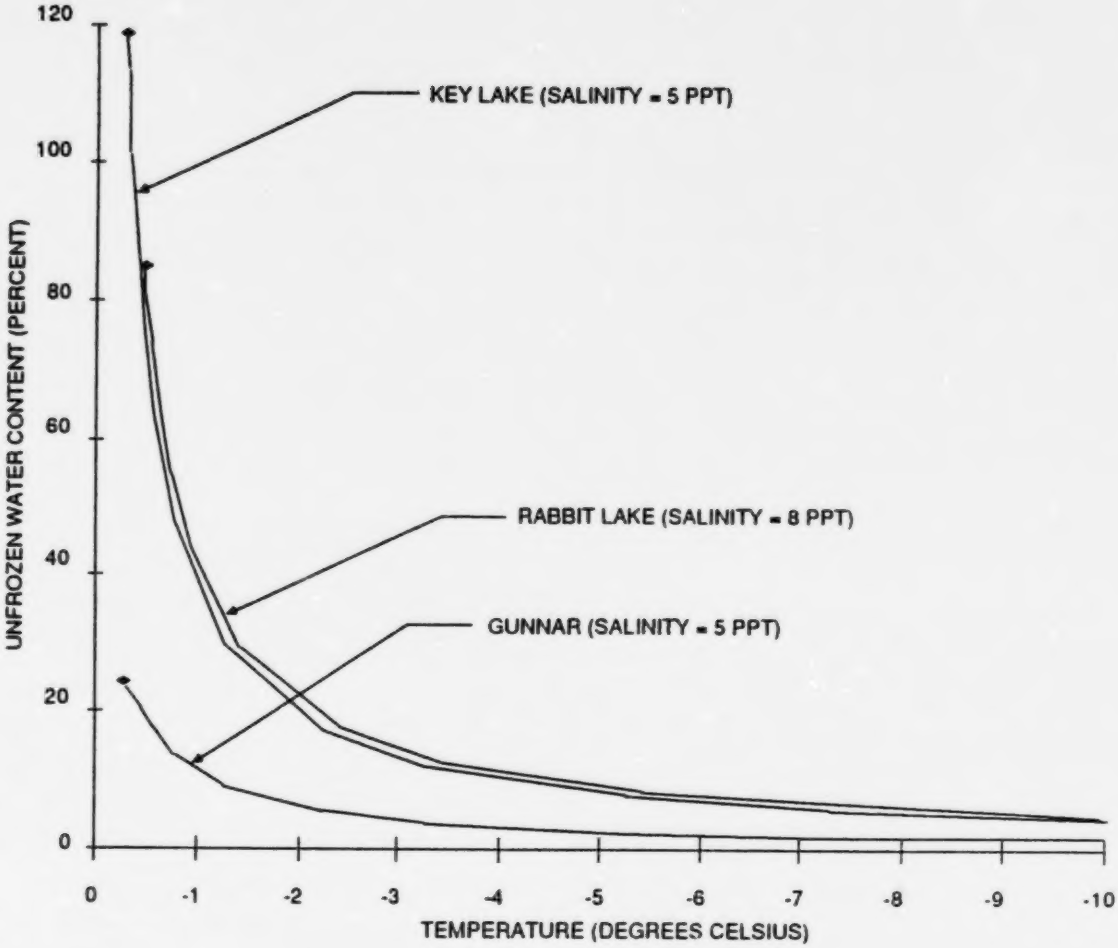


Figure 4.4-1 Typical Unfrozen Water Content Curves for Fine-Grained Tailings

4.4.2 GROUND SURFACE HEAT EXCHANGE CONDITIONS

The heat exchange occurring at the ground surface is a principal boundary condition in a geothermal problem. The net heat flux at the ground surface is the sum of net longwave radiation, net shortwave (solar) radiation, net convective heat flux and evapotranspiration, see Figure 3.2-2. The site data required to determine the components of the ground heat flux are actual meteorological conditions such as mean monthly air temperatures, wind speed, snow cover and solar radiation. Also required are the surface properties of the ground such as albedo (reflected solar radiation), emissivity and greenhouse factor. Evapotranspiration, the process of heat transfer as a result of moisture loss from vegetation and the ground surface, is input as a fraction of the semi-empirically determined monthly potential evapotranspiration (Thornthwaite 1948). The evapotranspiration factor can vary between 0 and 1, although a value of 0.5 is considered high.

The net transient heat flux into the ground is applied as a boundary condition in the finite element conduction code to determine the actual ground surface temperature. Figure 4.4-2 compares the mean monthly air temperatures for the Gunnar site with the monthly ground surface temperatures determined for two sets of surface conditions.

4.5 METHODOLOGY

Geothermal analyses were carried out for the Gunnar, Key Lake and Rabbit Lake tailings disposal sites using the GEOTHERM finite element program described above. Analyses were restricted to one-dimensional simulations. Two typical soil profiles were established for the Gunnar site, and these were analysed using normal climatic and surface conditions to serve as baseline cases for comparison with other sites. Since a reasonable amount of soil, climatic and ground temperature information is available for Gunnar (BBT 1986), this site was the subject of further detailed parametric and sensitivity analyses. A limited number of analyses were then performed for Key Lake and Rabbit Lake, for comparison with the trends established at Gunnar.

All analyses were conducted using generalized soil profiles (Chapter 2) and Environment Canada climatic data obtained from meteorological stations located near each site. The principal variables in the analyses were soil profile, snow depth, wind speed, evapotranspiration and initial ground temperature profile.

In the absence of sufficiently comprehensive and reliable natural ground temperature information, it is necessary to assume an initial condition for the analyses that may not be in thermal equilibrium with the environmental boundary conditions. As noted previously, this initial imbalance will produce a transient thermal response in the soil until steady state conditions are attained. The long-term thermal regime would be inferred from the steady state conditions predicted by the model, and not necessarily from the transient behaviour that is modelled. However, for the purposes of this project the long-term conditions were estimated based on the trends observed in a 25-year simulation, and only in one or two cases were longer runs made to confirm predicted trends. The following sections describe the analyses in detail.

4.6 DESCRIPTION OF ANALYSES

4.6.1 GUNNAR

For the Gunnar site, two typical soil profiles were selected for analysis. The profiles are shown on Figure 2.2-4 and the soil properties summarized in Tables 4.6-1 and 4.6-2 below. The first profile, typical of areas where relatively fine-grained tailings were deposited, contains 6 m of silt and sand tailings, overlying 5 m of clayey silt. The second profile, typical of areas with coarse-grained tailings, contains 14 m of sand and silt tailings, overlying 5 m of clayey silt. The clayey silt overlies bedrock in both profiles. The water table is 1 m below surface in the fine-grained profile, and 6 m below surface

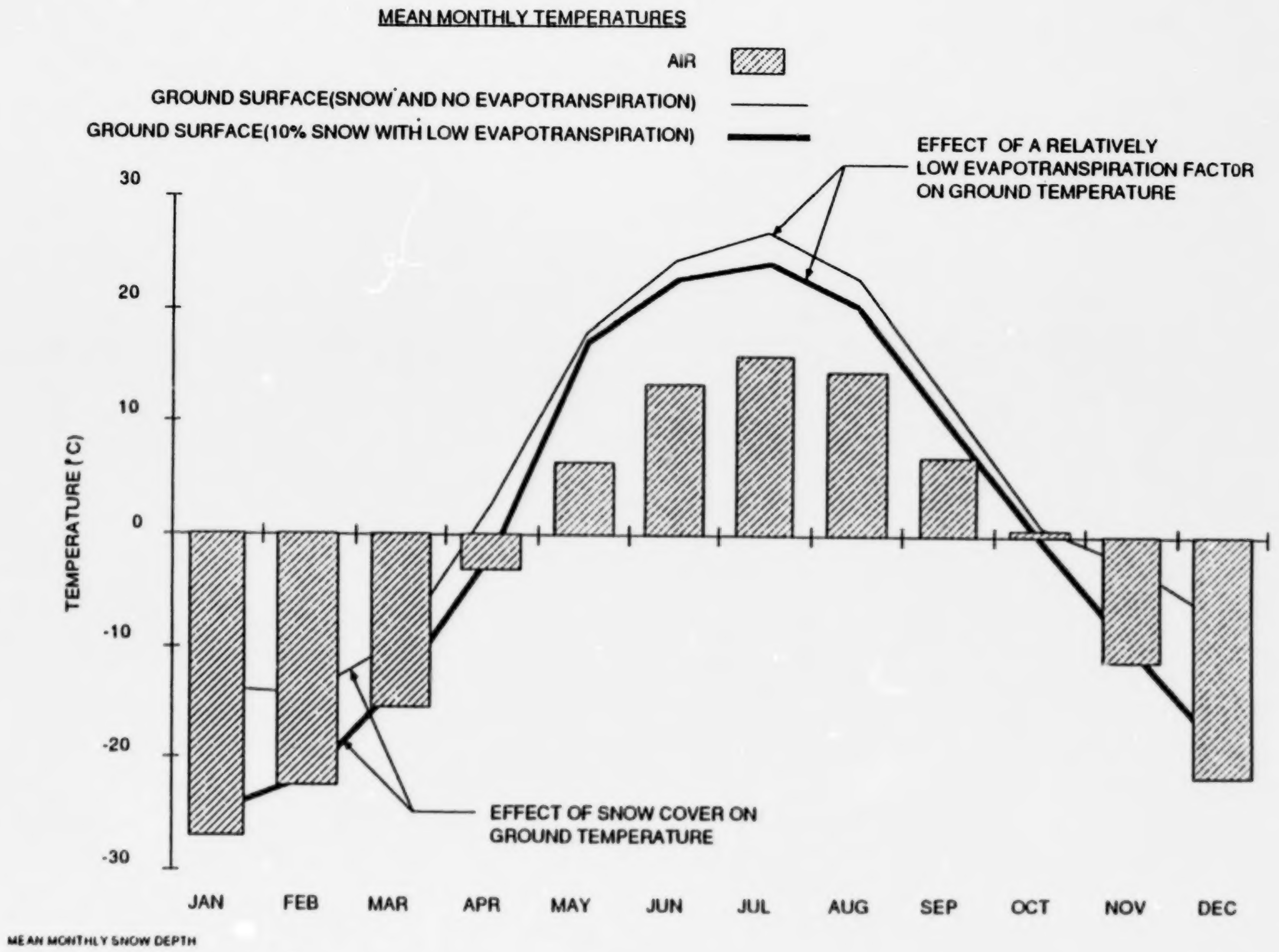


Figure 4.4-2 Influence of Selected Climatic Factors on Ground Surface Temperature

in the coarse-grained profile. Climatic data for the Gunnar area are summarized in Table 2.2-1. The surface thermal properties used are summarized in Table 4.6-3.

TABLE 4.6-1

SOIL PROPERTIES
GUNNAR FINE-GRAINED PROFILE

DEPTH INTERVAL (m)	0 - 1	1 - 6	6 - 11	11+
MATERIAL DESCRIPTION	Fine Tailings	Fine Tailings	Clayey Silt	Bedrock
Above/below water table	Above	Below	Below	Below
Clay Fraction (%)	4.0	4.0	23.0	0.0
Water Content (%)	10.0	24.0	40.0	5.0
Dry Density (Mg/m^3)	1.33	1.65	1.29	2.20
Freezing Point (°C)	0.27	0.27	0.11	0.00
Quartz Content (%)	60.0	60.0	45.0	75.0
Specific Surface Area (m^2/g)	10.0	10.0	60.0	0.05
Pore Water Salinity (ppt)	5.0	5.0	2.0	0.0
Thermal Conductivity (W/m°C)				
Frozen	0.80	2.60	2.41	2.75
Unfrozen	0.65	1.65	1.32	2.72
Specific Heat (kJ/kg°C)				
Frozen	0.93	1.08	1.25	0.71
Unfrozen	1.05	1.40	1.72	0.75
Latent Heat at 20°C (MJ/m^3)	41.0	128.0	155.0	37.0

A total of ten scenarios were analyzed for the Gunnar site. The baseline analysis for each profile utilized normal air temperature, wind speed and snow depth, with no evapotranspiration, and considered initial ground temperatures to be 0°C at all depths. Sensitivity analyses were performed with varying snow depth and/or wind speed, and with evapotranspiration representative of vegetation cover. One run was performed with the initial ground temperatures set at -2°C.

Eleven analyses were performed for the Gunnar site and the results are summarized in Table 4.6-4. The analyses show that, for the two profiles investigated, the dominant factors affecting the thermal regime are the depth of snow cover and evapotranspiration. Wind speed is less significant for the cases analyzed. Snow depth and evapotranspiration can vary locally according to ground surface conditions, and may be modified by imposed measures. Snow depth is affected by type of vegetation and site exposure. Evapotranspiration is a function of the vegetation and drainage characteristics at ground surface. Much of the Gunnar site lacks vegetation and has free-draining surface soils, contributing to low evapotranspiration.

Analyses G1, G2 and G5 (Figures 4.6-1, 2 and 3) indicate that without the evapotranspiration effect, a small net heat gain occurs at ground surface for normal and 10 percent snow depths, both for fine- and coarse-grained profiles. Consequently, the tailings below the seasonal frost depth eventually reach an unfrozen state irrespective of either the initial thermal condition or the particle size distribution of the tailings. The reduced snow depth creates a marked increase in the depth of the seasonal frost penetration. Field observations in March, 1985, indicate frost depths ranging between 0.6 and 4.4 m. Snow depths of up to 1 m were noted, in contrast to the monthly average of roughly 0.25 m used in the analysis.

TABLE 4.6-2

SOIL PROPERTIES
GUNNAR COARSE-GRAINED PROFILE

DEPTH INTERVAL (m)	0 - 1	1 - 6	6 - 14	14 - 19	19+
MATERIAL DESCRIPTION	Coarse Tailings	Coarse Tailings	Coarse Tailings	Clayey Silt	Bedrock
Above/below water table	Above	Above	Below	Below	Below
Clay Fraction (%)	6.0	6.0	6.0	23.0	0.0
Water Content (%)	5.0	13.0	20.0	40.0	5.0
Dry Density (Mg/m^3)	1.33	1.55	1.75	1.29	2.20
Freezing Point (°C)	0.27	0.27	0.27	0.11	0.00
Quartz Content (%)	60.0	60.0	60.0	45.0	75.0
Specific Surface Area (m^2/g)	15.0	15.0	15.0	60.0	0.05
Pore Water Salinity (ppt)	5.0	5.0	5.0	2.0	0.0
Thermal Conductivity (W/m°C)					
Frozen	0.54	1.58	3.21	2.41	2.75
Unfrozen	0.68	1.44	2.10	1.32	2.72
Specific Heat (kJ/kg°C)					
Frozen	0.84	0.96	1.07	1.25	0.71
Unfrozen	0.90	1.13	1.40	1.72	0.75
Latent Heat at 20°C (MJ/m^3)	19.0	63.0	113.0	155.0	37.0

TABLE 4.6-3

SURFACE THERMAL PROPERTIES
GUNNAR SITE

1.	SNOW COVER:	Thermal conductivity	0.31 W/m°C
		Surface emissivity	0.90
		Surface absorptivity	0.50
2.	GROUND SURFACE:	Surface emissivity	0.90
		Surface absorptivity	0.75

Analysis G3 (Figures 4.6-4 and 5) shows that if the lower bound value of snow depth is modelled with a small evapotranspiration factor (0.2), a net heat loss from the ground results and aggrading permafrost is initiated in fine-grained tailings. Analysis G6 (Figure 4.6-6), however, shows that, for the coarse-grained tailings profile with the same surface conditions, the depth of seasonal frost penetration becomes greater, but there is no aggradation of permafrost. The 6 m of coarse-grained tailings above the water table have an insulating effect.

Meteorological data reported by BBT (1986) suggest that wind speeds at the Gunnar tailings site may be greater than those noted at the airport in Uranium City. To address this, wind speeds were increased by 50 percent in analyses G7, G8 and G9. Figures 4.6-7, 8 and 9 illustrate that higher wind speeds reduce the ground temperatures, however, the combined effect of evapotranspiration and reduced snow depths remains a prerequisite for permafrost aggradation.

Current evidence exists that both unfrozen tailings, and stable or aggrading permafrost coexist at Gunnar. The natural undulating surface of the tailings site, combined with variations in plant growth and soil gradations, give rise to snow drifting and evapotranspiration effects that both enhance and retard permafrost aggradation. In general, only seasonal frost is observed. However, permafrost

TABLE 4.6-4

SUMMARY OF THERMAL ANALYSES
GUNNAR SITE

ANALYSIS NUMBER	FIGURE NUMBER	TAILINGS PROFILE	INITIAL GROUND TEMPERATURE	WIND SPEED	SNOW DEPTHS	EVAPOTRANSPIRATION	PREDICTED GEOTHERMAL CONDITIONS	SEASONAL FREEZE/THAW DEPTH (m)	YEARS FOR TAILINGS TO FREEZE (THAW)
G1	4.6-1	Fine	0°C	Normals	Normals	0.0	Seasonal Freezing	2.2	-
G2	4.6-2	Fine	0°C	Normals	10 percent	0.0	Seasonal Freezing	5.2	-
G3	4.6-4 & -5	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	3.0	21
G4	4.6-11	Fine	-2°C	Normals	Normals	0.0	Permafrost Degradation/ Seasonal Freezing	2.4	(9)
G5	4.6-3	Coarse	0°C	Normals	Normals	0.0	Seasonal Freezing	2.7	-
G6	4.6-6	Coarse	0°C	Normals	10 percent	0.2	Seasonal Freezing	4.0	-
G7	4.6-7	Fine	0°C	1.5 x	Normals	0.0	Seasonal Freezing	2.5	-
G8	4.6-8	Fine	0°C	1.5 x	Normals	0.2	Seasonal Freezing	2.9	-
G9	4.6-9	Fine	0°C	1.5 x	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	2.0	4
G10	4.6-10	Fine	0°C	Normals	Normals	0.5	Seasonal Freezing	3.1	-

appears to coincide with features described by BBT (1986) as "mounds". Mounds are believed to originate where there are fine-grained tailings, topographic highs and a high water table. A reduced snow cover at these locations, coupled with a small amount of evapotranspiration are sufficient to initiate aggrading permafrost. Migration of water to the freezing front results in frost heave and consequent growth of the mound. Through this process the mounds become self-perpetuating. The mounds at Gunnar are reported to be frozen to a depth of approximately 5 m with discrete layers of ice at depth.

Analysis G10 (Figure 4.6-10) examines the effect of long-term revegetation with spruce trees. Although a forest of spruce trees greatly increases evapotranspiration (a factor of 0.5 was assumed), this cooling effect is partly offset by the full snow depth that would be assured by the protection of the trees. A small net heat gain still results at ground surface, although the depth of seasonal freezing is somewhat greater than in the baseline case.

As noted, analysis of natural climatic and surface conditions at Gunnar indicates an overall heat gain by the ground. The effect of this is not immediately apparent from the above analyses since the initial ground condition is unfrozen (0°C). To investigate the warming effect on initially frozen ground, analysis G4 (Figure 4.6-11) was performed for an initial ground temperature of -2°C. Since frozen tailings are frequently reported to have layers of discrete ice, a high moisture content was assumed, similar to the tailings properties at the Key Lake site (described in section 4.6-2). The thaw front advances into the tailings at approximately 0.5 m per year, and the tailings are completely thawed within 9 years. A stable thawed condition is attained throughout the soil profile after approximately 15 years.

Since the long-term ground temperature variation is not immediately apparent from the freezing isotherms shown in the figures referenced above, Figure 4.6-12 presents the variation of temperature with time for a point at approximately the mid-depth of the tailings. The variations are shown for three of the analyses, in which gradual warming, aggrading permafrost, and thawing permafrost are represented respectively.

In summary, the analyses are consistent with observations made at Gunnar. Normal depths of snow cover generally prevent the development of permafrost. Where snow depths are much less than the normals due to drifting, evapotranspiration can cause a net heat loss at ground surface that will result in permafrost aggradation. The rate at which permafrost aggradation or degradation will occur is determined by a combination of site-specific soil and microclimatic factors. The foregoing analyses are based only on general data and not calibrated with measured soil temperature profiles and therefore are indicative of trends. Permafrost appears only in the local mounds at Gunnar and a rigorous determination of aggradation rates requires consideration of three-dimensional effects and limitations imposed by rates of moisture migration. It is anticipated that the geothermal conditions at Gunnar are close to a state of equilibrium and will prevail until surface conditions are altered.

4.6.2 KEY LAKE

The soil profile adopted for analysis of the Key Lake tailings site is shown on Figure 2.3-4. Table 4.6-5 summarizes the soil properties used in the analysis. The profile comprises 4 m of low density fine-grained tailings overlying a silty till to a depth of 8 m. The till is underlain by bedrock. The water table at this site is assumed to be at or close to the ground surface. Meteorological conditions are summarized in Table 2.3-1 and surface thermal properties used in the analysis are summarized in Table 4.6-6.

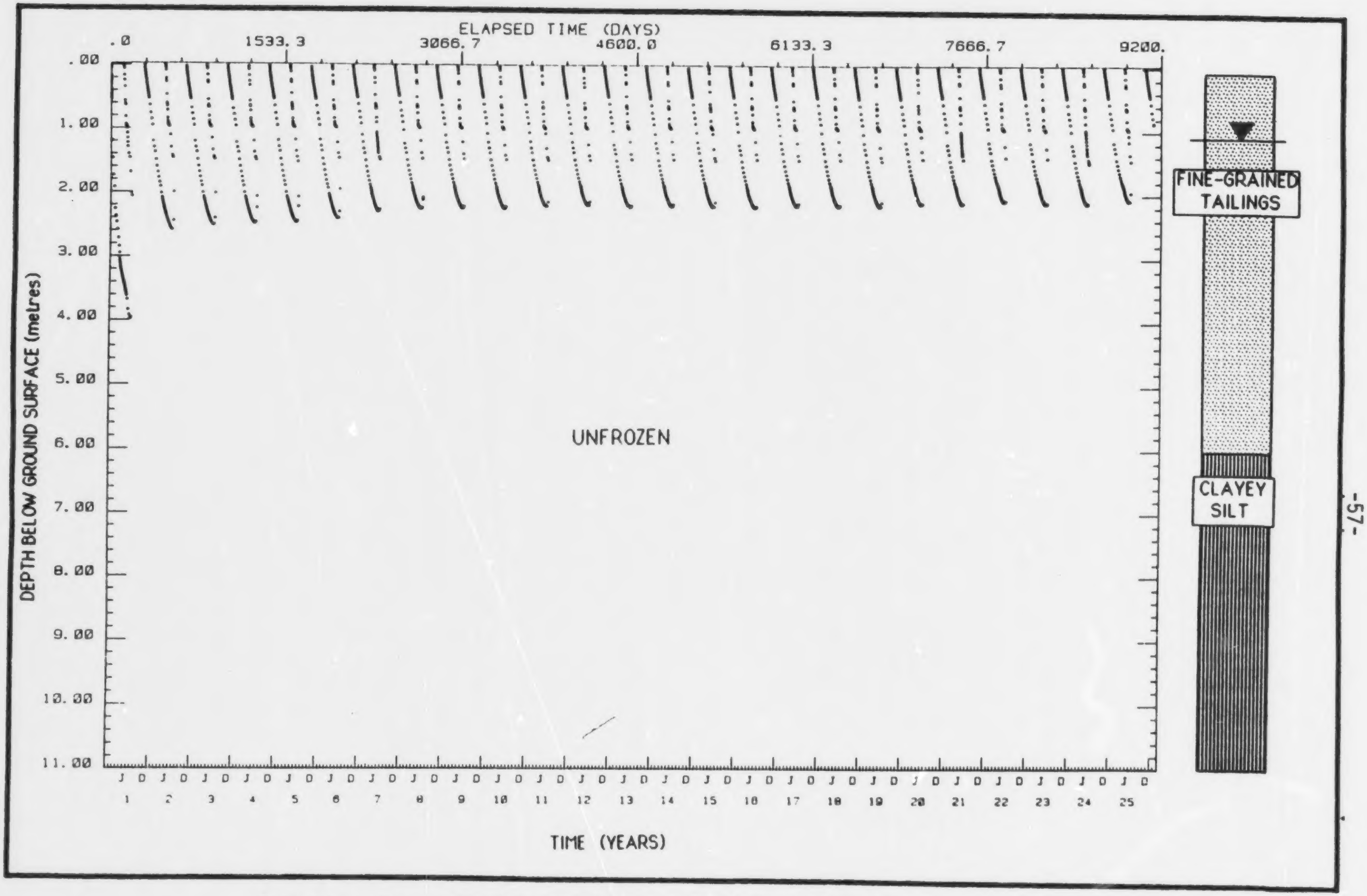


FIGURE 4.6-1 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING NORMAL CLIMATIC CONDITIONS AND NO EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS) - FINE TAILINGS

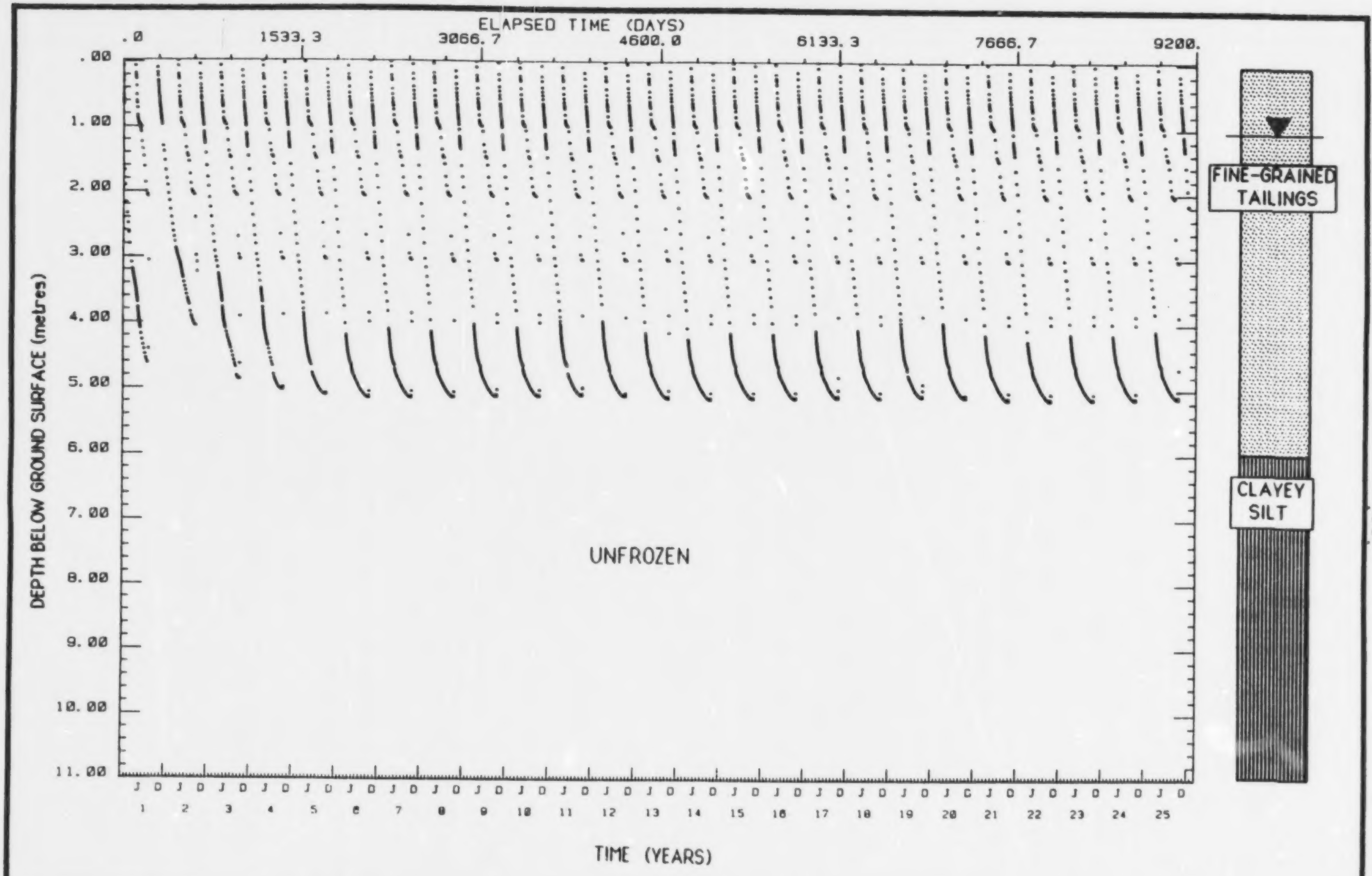


FIGURE 4.6-2 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE
ASSUMING 10 PERCENT OF NORMAL SNOW COVER
AND NO EVAPOTRANSPIRATION EFFECTS
(0 TO 25 YEARS) - FINE TAILINGS

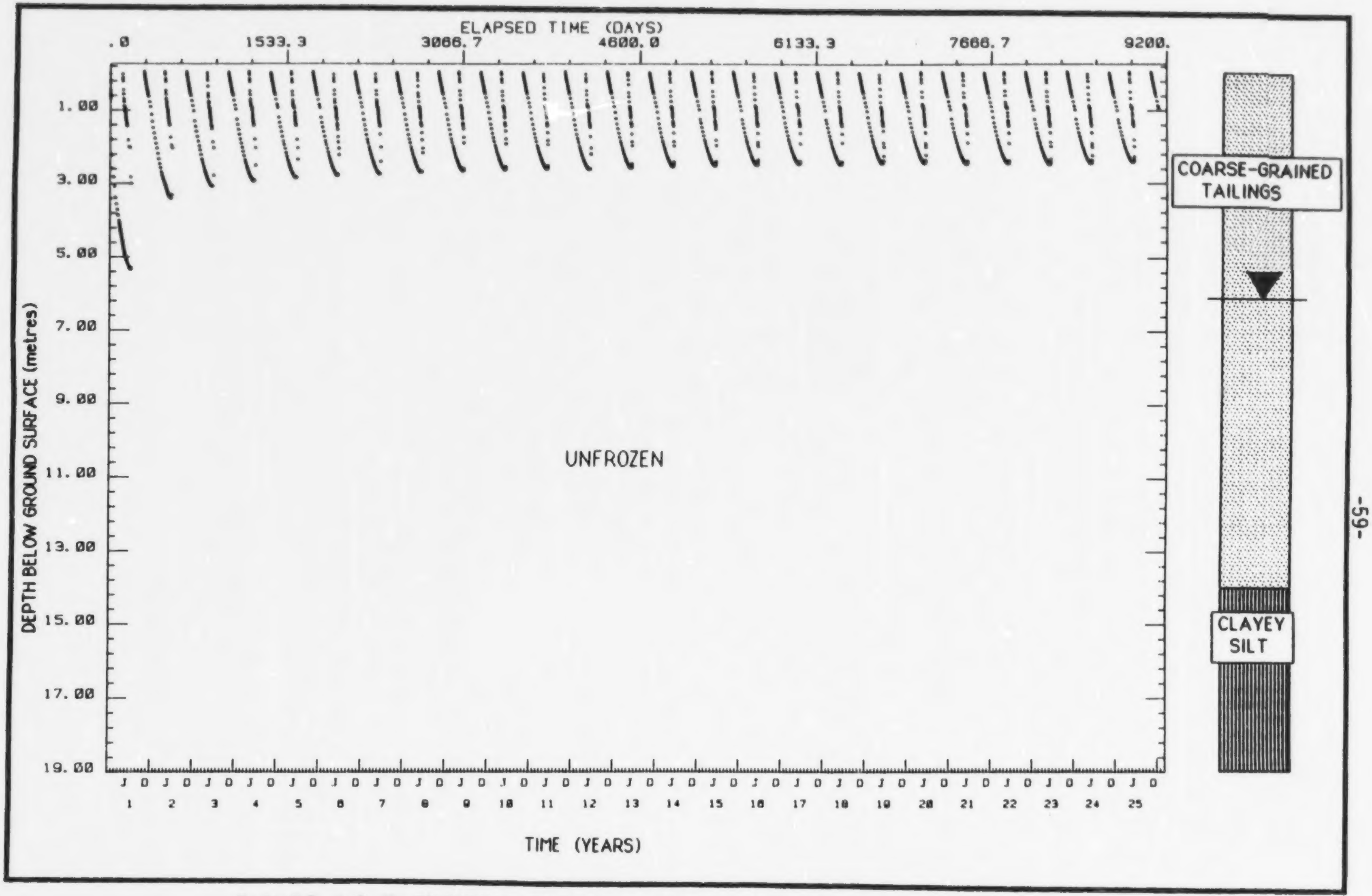


FIGURE 4.6-3 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING NORMAL CLIMATIC CONDITIONS AND NO EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS) - COARSE TAILINGS

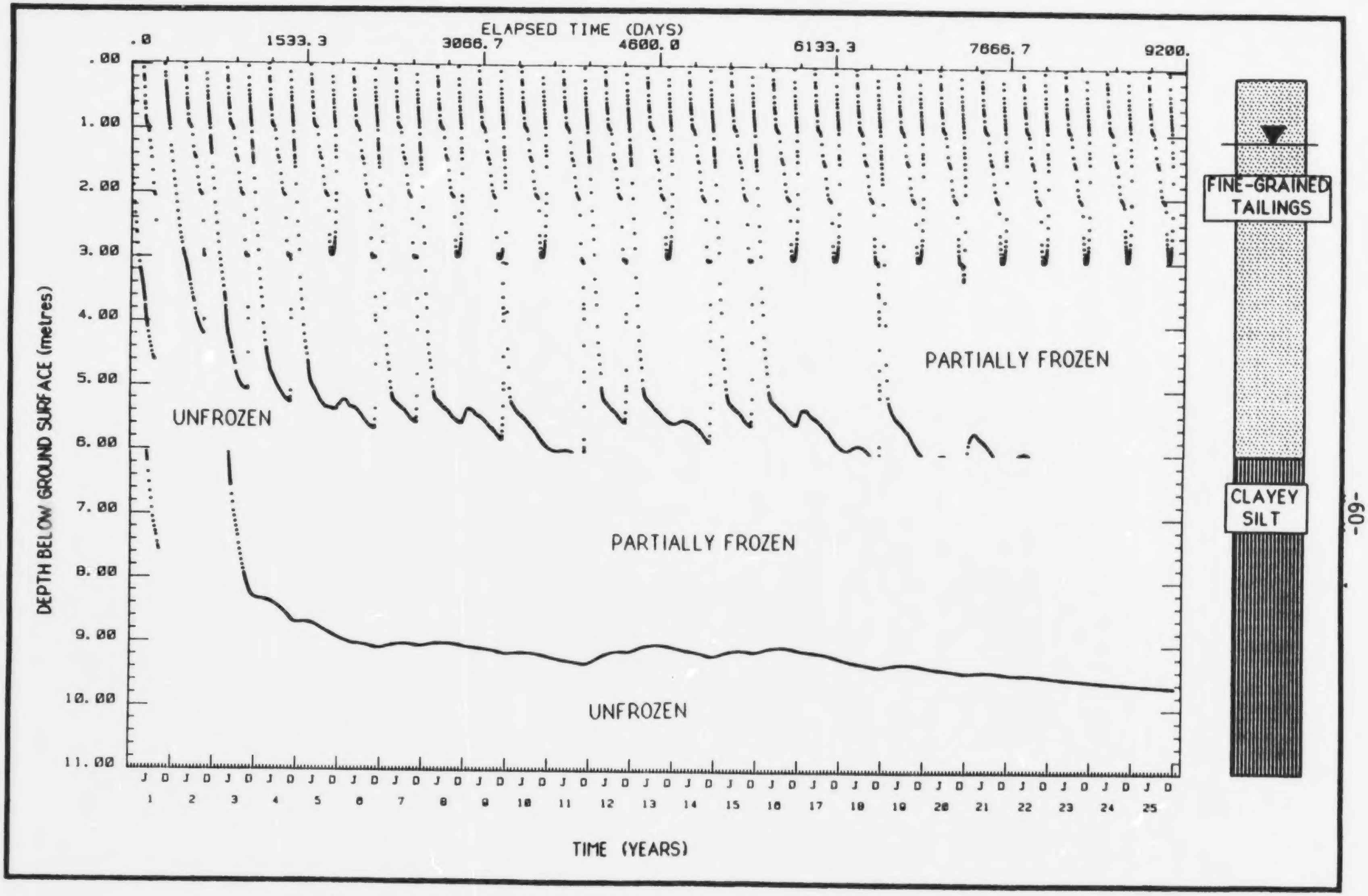


FIGURE 4.6-4 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING 10 PERCENT OF NORMAL SNOW COVER WITH EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS) - FINE TAILINGS

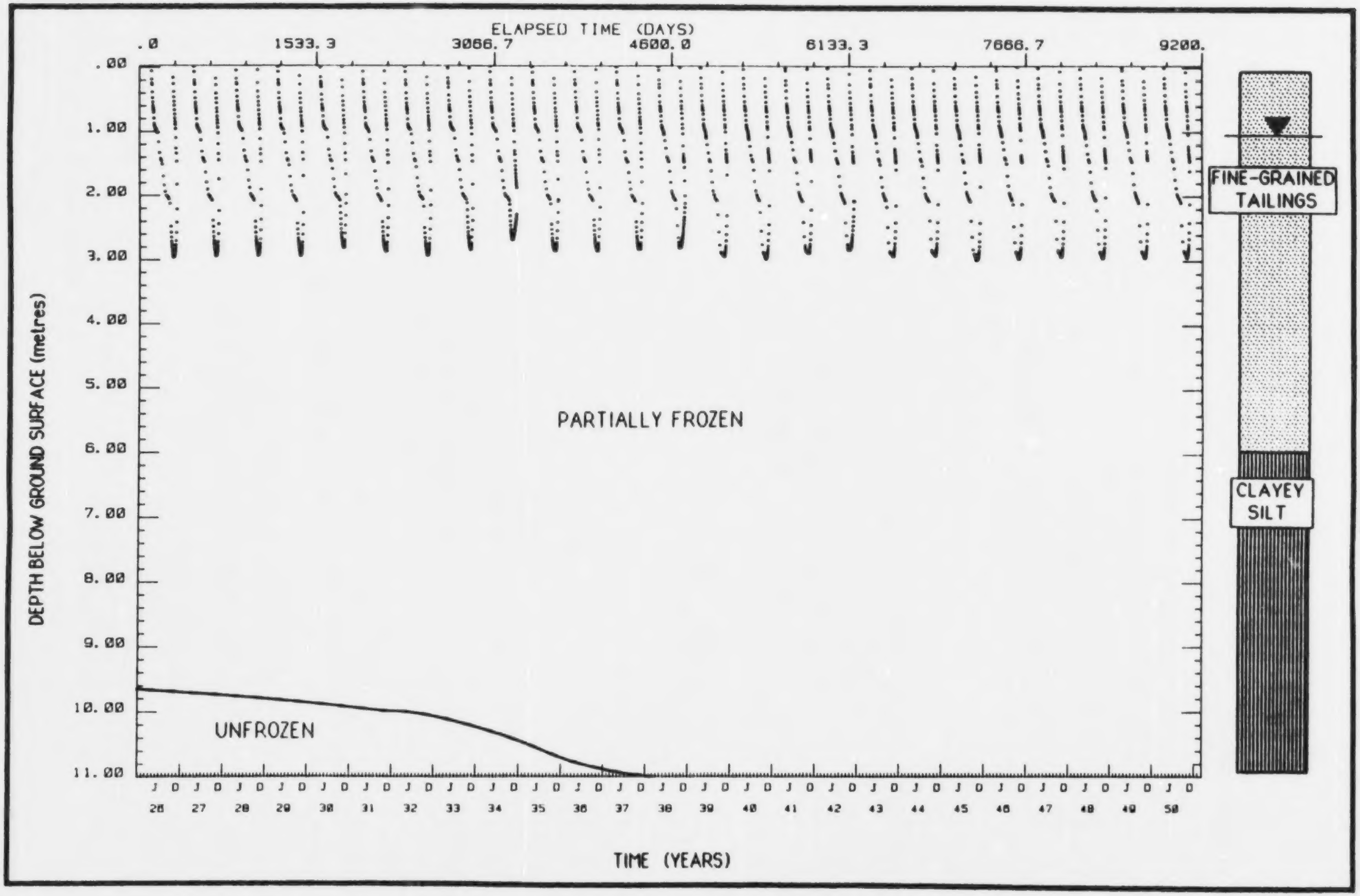


FIGURE 4.6-5 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING 10 PERCENT OF NORMAL SNOW COVER WITH EVAPOTRANSPIRATION EFFECTS (25 TO 50 YEARS)-FINE TAILINGS

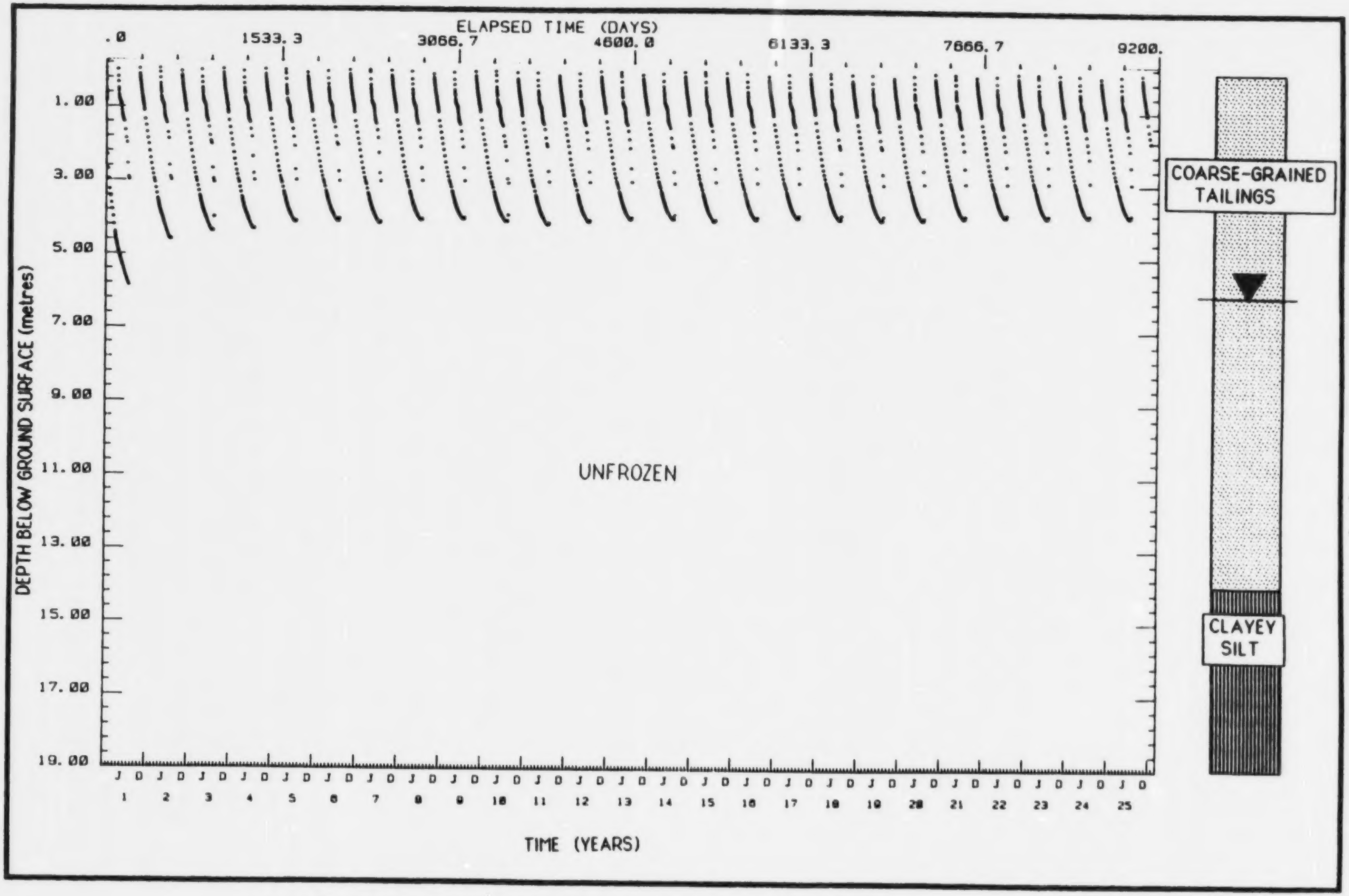


FIGURE 4.6-6 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING 10 PERCENT OF NORMAL SNOW COVER WITH EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS) - COARSE TAILINGS

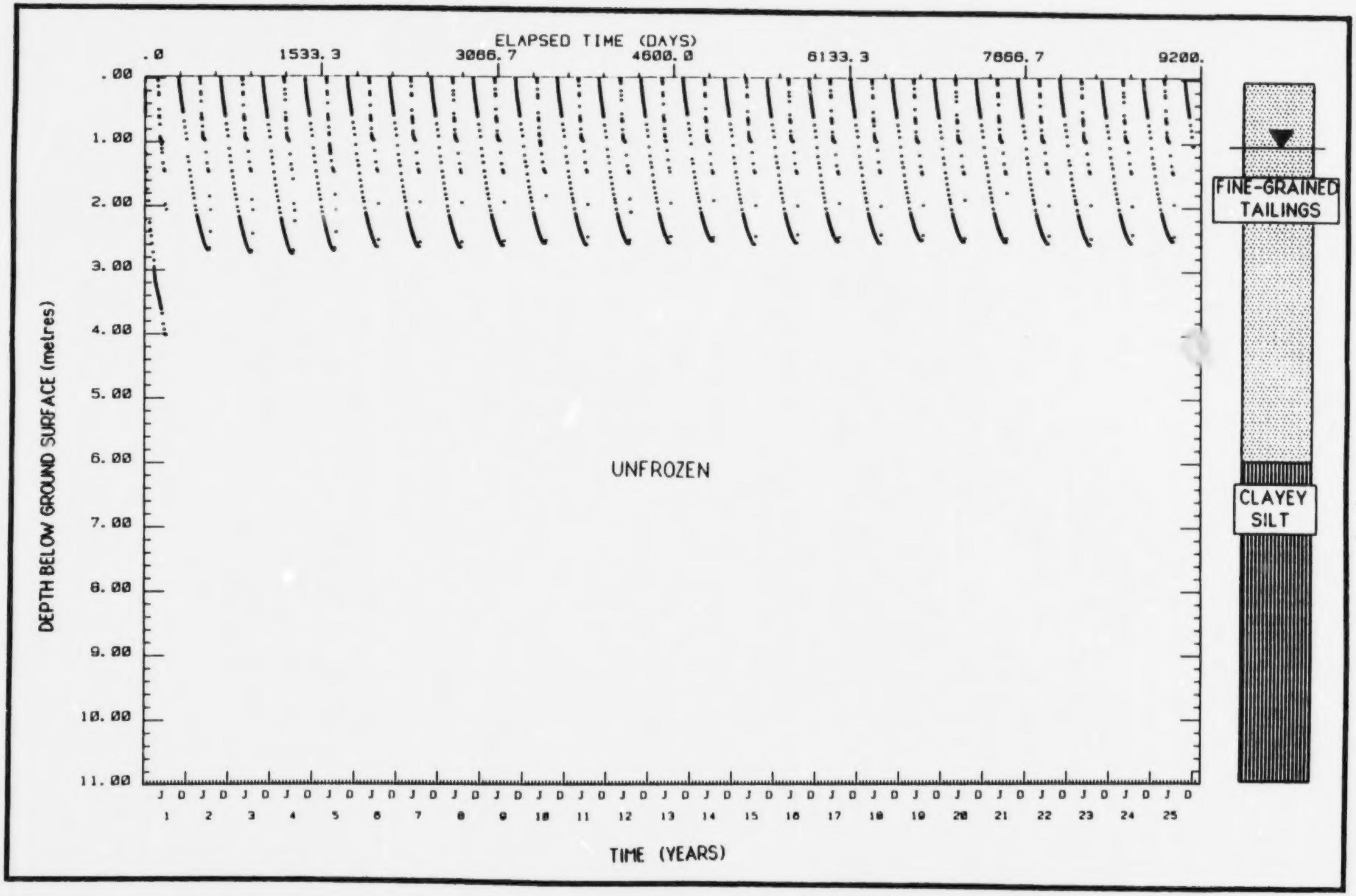


FIGURE 4.6-7 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING NORMAL CLIMATIC CONDITIONS, WITH NO EVAPOTRANSPIRATION EFFECTS AND HIGH WIND SPEEDS (0 TO 25 YEARS) - FINE TAILINGS

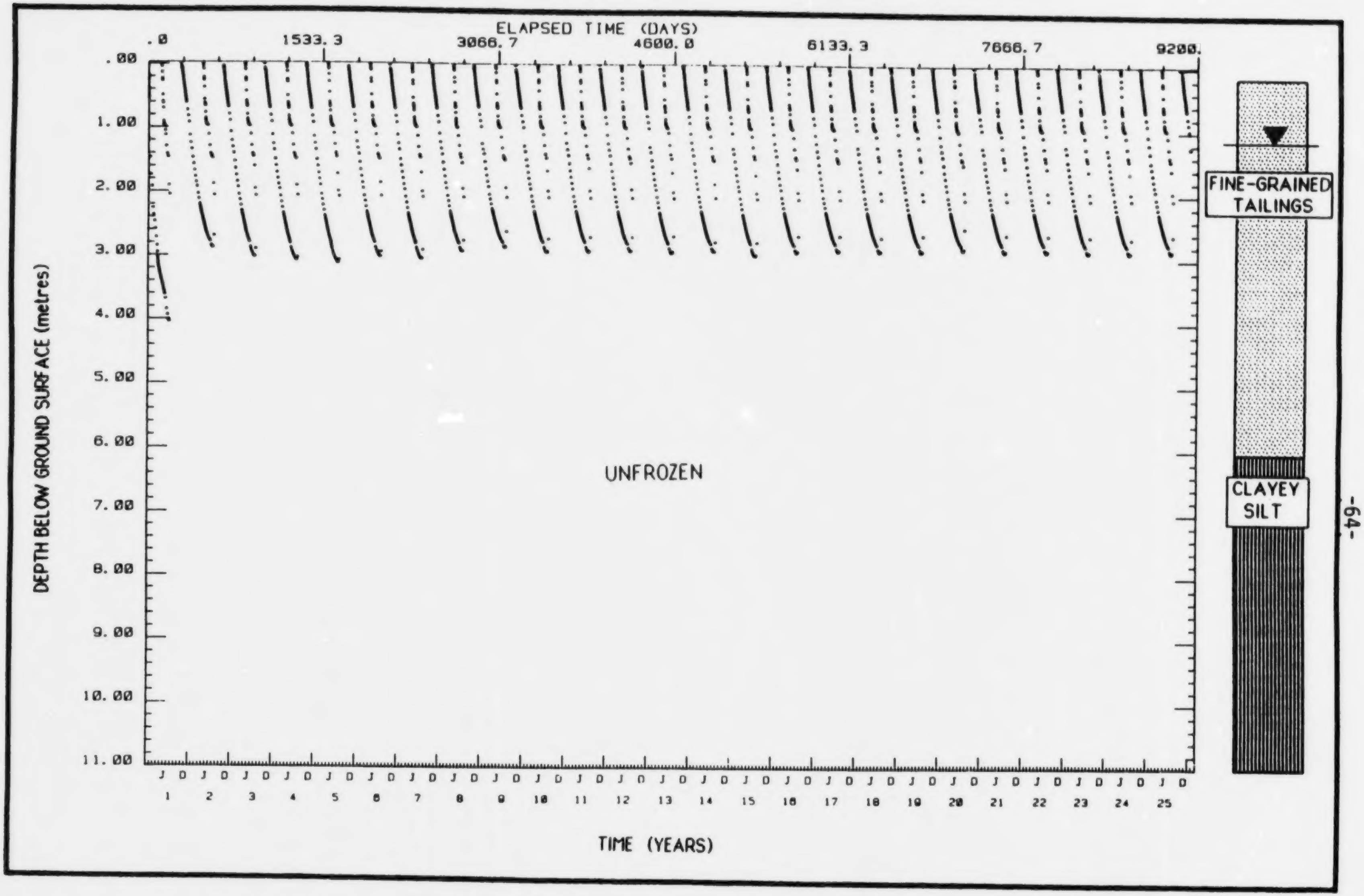


FIGURE 4.6-8 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING NORMAL CLIMATIC CONDITIONS, WITH EVAPOTRANSPIRATION EFFECTS AND HIGH WIND SPEEDS (0 TO 25 YEARS) - FINE TAILINGS

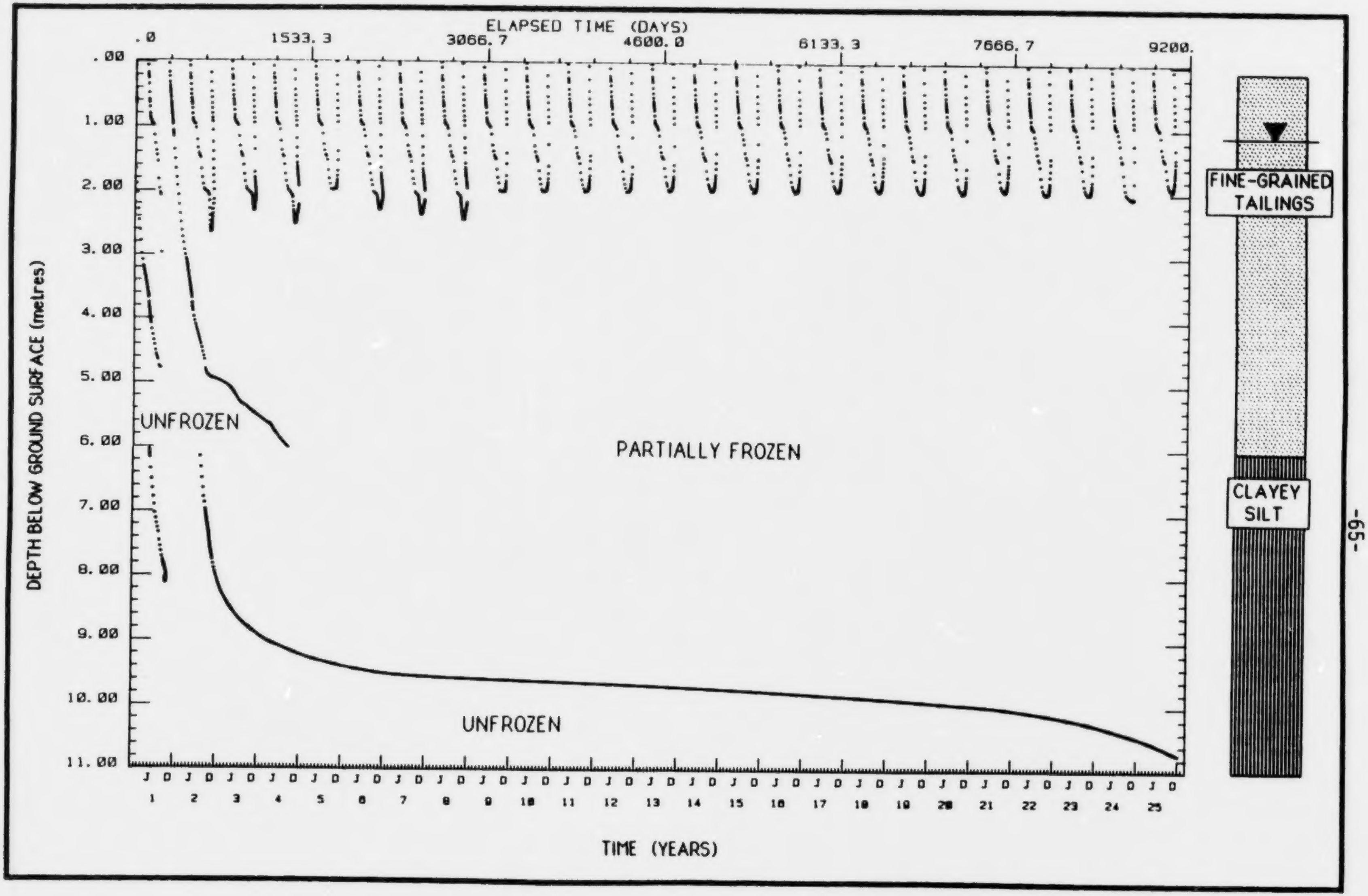


FIGURE 4.6-9 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING 10 PERCENT OF NORMAL SNOW COVER, EVAPOTRANSPIRATION EFFECTS AND HIGH WIND SPEEDS (0 TO 25 YEARS) - FINE TAILINGS

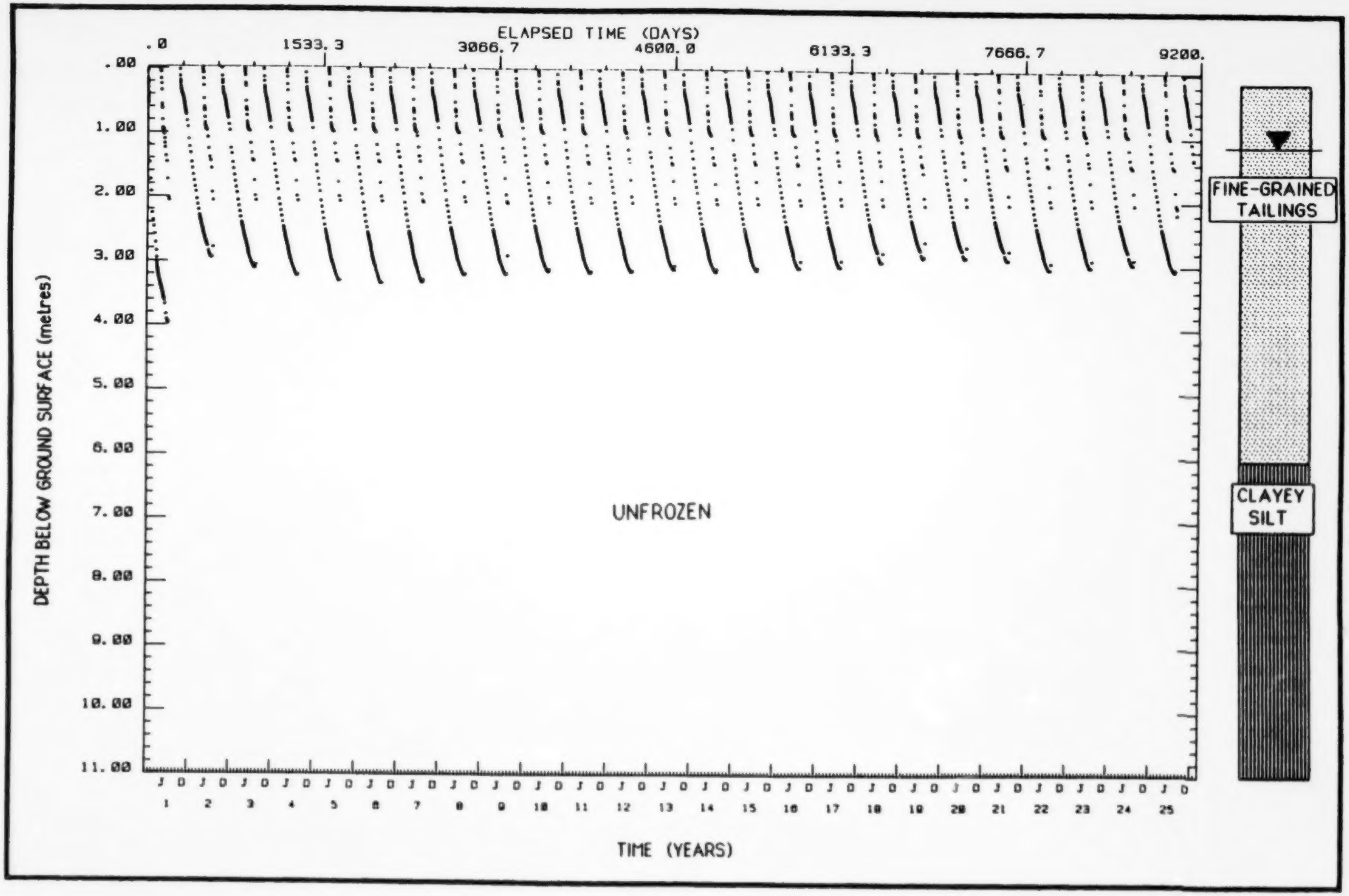


FIGURE 4.6-10 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE ASSUMING NORMAL CLIMATIC CONDITIONS AND EVAPOTRANSPIRATION EFFECTS ASSOCIATED WITH REFORESTING THE TAILINGS POND (0 TO 25 YEARS), FINE TAILINGS

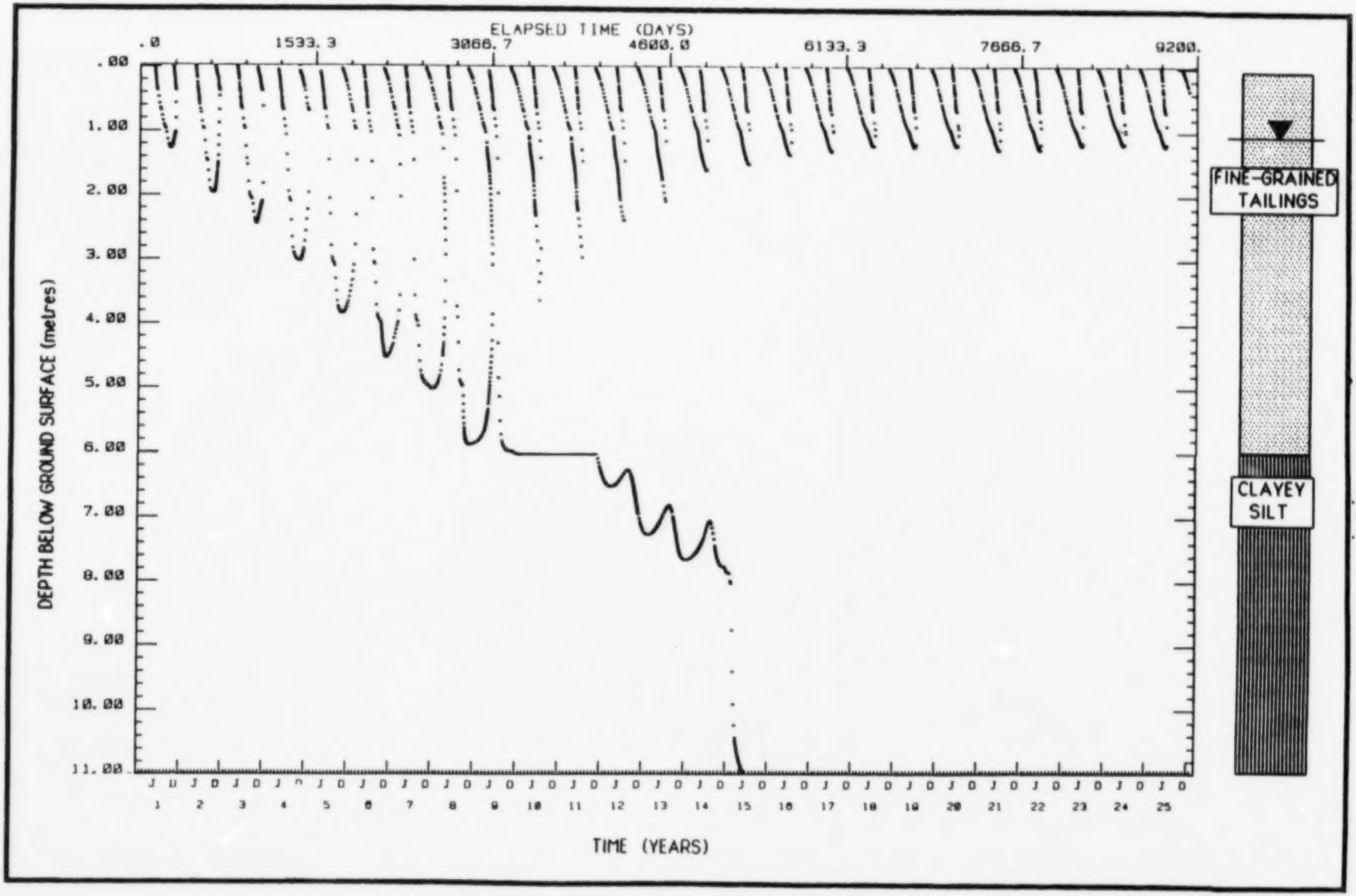


FIGURE 4.6-11 FREEZING ISOTHERM WITH TIME AT GUNNAR SITE
ASSUMING THAT THE TAILINGS ARE ORIGINALLY FROZEN (-2 C),
NORMAL CLIMATIC CONDITIONS EXIST
AND NO EVAPOTRANSPIRATION EFFECTS
(0 TO 25 YEARS)

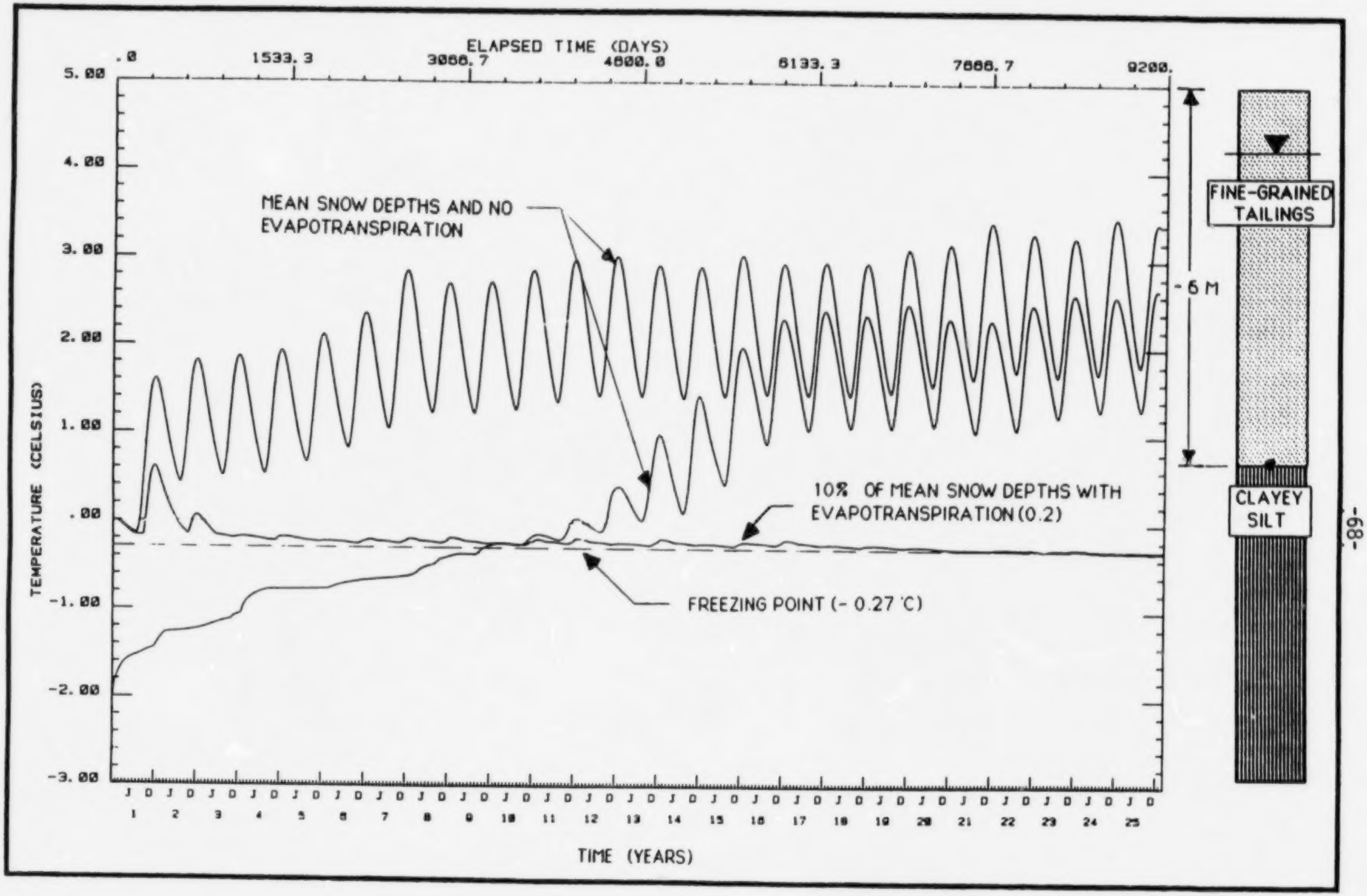


FIGURE 4.6-12 TEMPERATURE WITH TIME AT 6 METRES PENETRATION - FINE-GRAINED TAILINGS PROFILE AT GUNNAR SITE

TABLE 4.6-5

SOIL PROPERTIES
KEY LAKE PROFILE

DEPTH INTERVAL (m)	0 - 4	4 - 8	8+
MATERIAL DESCRIPTION	Fine Tailings	Till	Bedrock Fine
Above/below water table	Below	Below	Below
Clay Fraction (%)	13.0	2.0	0.0
Water Content (%)	118.0	6.0	5.0
Dry Density (Mg/m^3)	0.64	1.90	2.20
Freezing Point (°C)	0.27	0.0	0.0
Quartz Content (%)	38.0	60.0	75.0
Specific Surface Area (m^2/g)	30.0	10.0	0.05
Pore Water Salinity (ppt)	5.0	0.0	0.0
Thermal Conductivity (W/m°C)			
Frozen	2.14	1.69	2.75
Unfrozen	0.80	1.71	2.72
Specific Heat (kJ/kg°C)			
Frozen	1.60	0.85	0.71
Unfrozen	2.60	0.93	0.75
Latent Heat at 20°C (MJ/m^3)	248.0	33.0	37.0

TABLE 4.6-6

SURFACE THERMAL PROPERTIES
KEY LAKE SITE

1. SNOW COVER:	Thermal conductivity	0.31 W/m°C
	Surface emissivity	0.90
	Surface absorptivity	0.50
2. BARE GROUND SURFACE: (no snow)	Surface emissivity	0.90
	Surface absorptivity	0.75

Four analyses were performed for the Key Lake site. The variables and main results are summarized in Table 4.6-7. Normal wind speeds and air temperatures were adopted, and snow depth and evapotranspiration factors were varied. An initial ground temperature of 0°C was used for three of the runs.

Analysis K1 (Figure 4.6-13) is based on mean monthly snow depths and zero evapotranspiration. The analysis predicts a seasonal frost penetration depth of approximately 1.3 m, which is consistent with a small net heat gain. Analysis K2 (Figure 4.6-14) considers a reduced snow depth and a small degree of evapotranspiration (0.2) consistent with surface vegetation. This condition produces a net heat loss, and hence permafrost aggradation. For these scenarios, results are similar to those for the Gunnar site. It should be noted that, for these analyses, the underlying till is initially partially frozen at 0°C, since the freezing point for this material is not depressed.

Although the existing water table is at or close to the surface in the Key Lake profile, the above analyses do not consider the full evaporation effect of a water table at surface. These analyses represent a long-term scenario in which drainage occurs thereby lowering the water table. Analysis K3 (Figure 4.6-15) used a high evapotranspiration factor (0.5) to account for the short-term condition.

TABLE 4.6-7

SUMMARY OF THERMAL ANALYSES
KEY LAKE SITE

ANALYSIS NUMBER	FIGURE NUMBER	TAILINGS PROFILE	INITIAL GROUND TEMPERATURE	WIND SPEED	SNOW DEPTHS	EVAPOTRANS-PIRATION	PREDICTED GEOTHERMAL CONDITIONS	SEASONAL FREEZE/THAW DEPTH (m)	YEARS FOR TAILINGS TO FREEZE (THAW)
K1	4.6-13	Fine	0°C	Normals	Normals	0.0	Seasonal Freezing	1.3	-
K2	4.6-14	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost/ Seasonal Thawing	1.3	4
K3	4.6-15	Fine	0°C	Normals	50 percent	0.5	Aggrading Permafrost/ Seasonal Thawing	1.7	4
K4	4.6-16	Fine	-2°C	Normals	Normals	0.0	Permafrost Degradation/ Seasonal Freezing	1.3	(13)

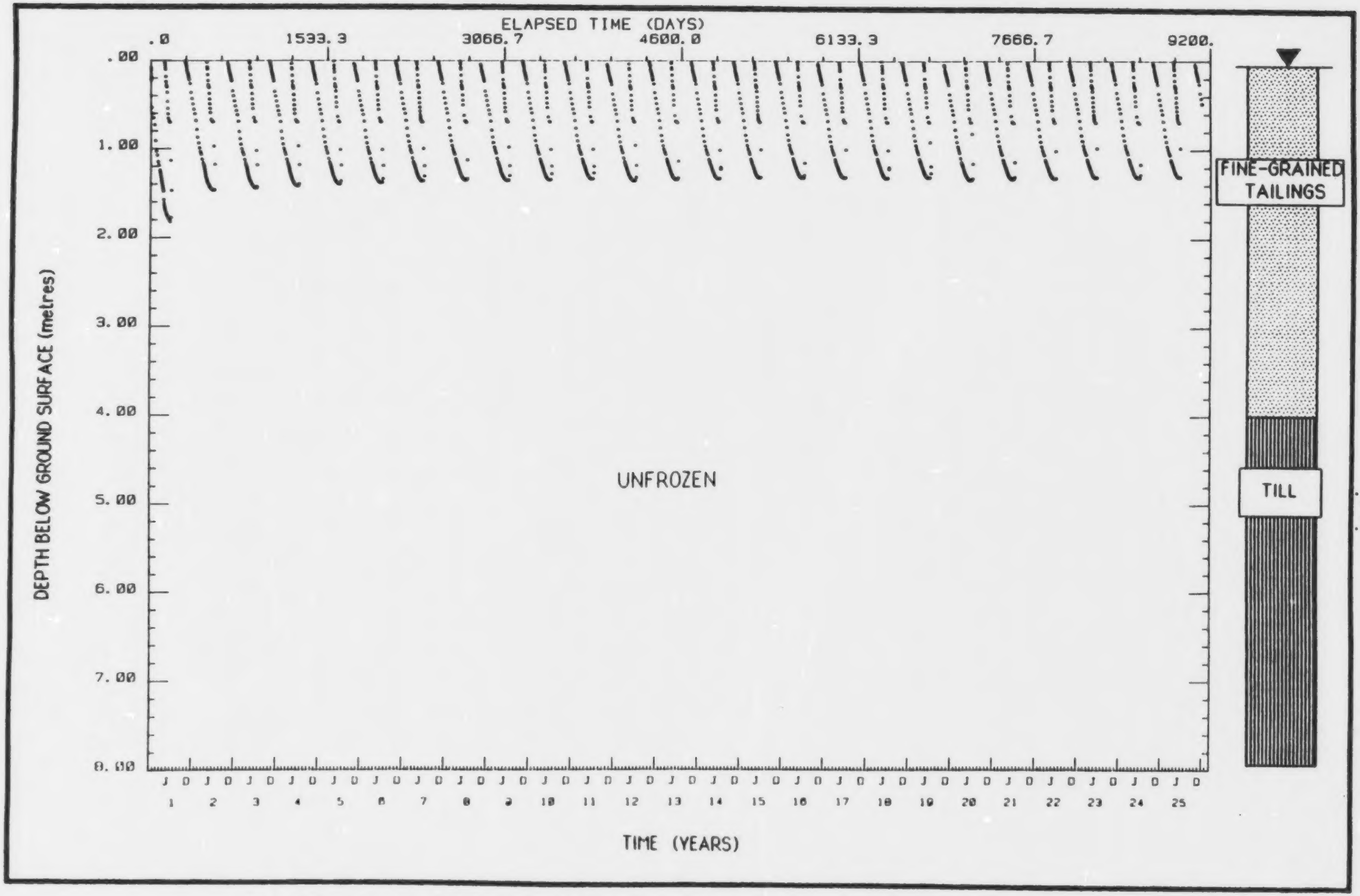


FIGURE 4.6-13 FREEZING ISOTHERM WITH TIME AT KEY LAKE SITE ASSUMING NORMAL CLIMATIC CONDITIONS AND NO EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS)

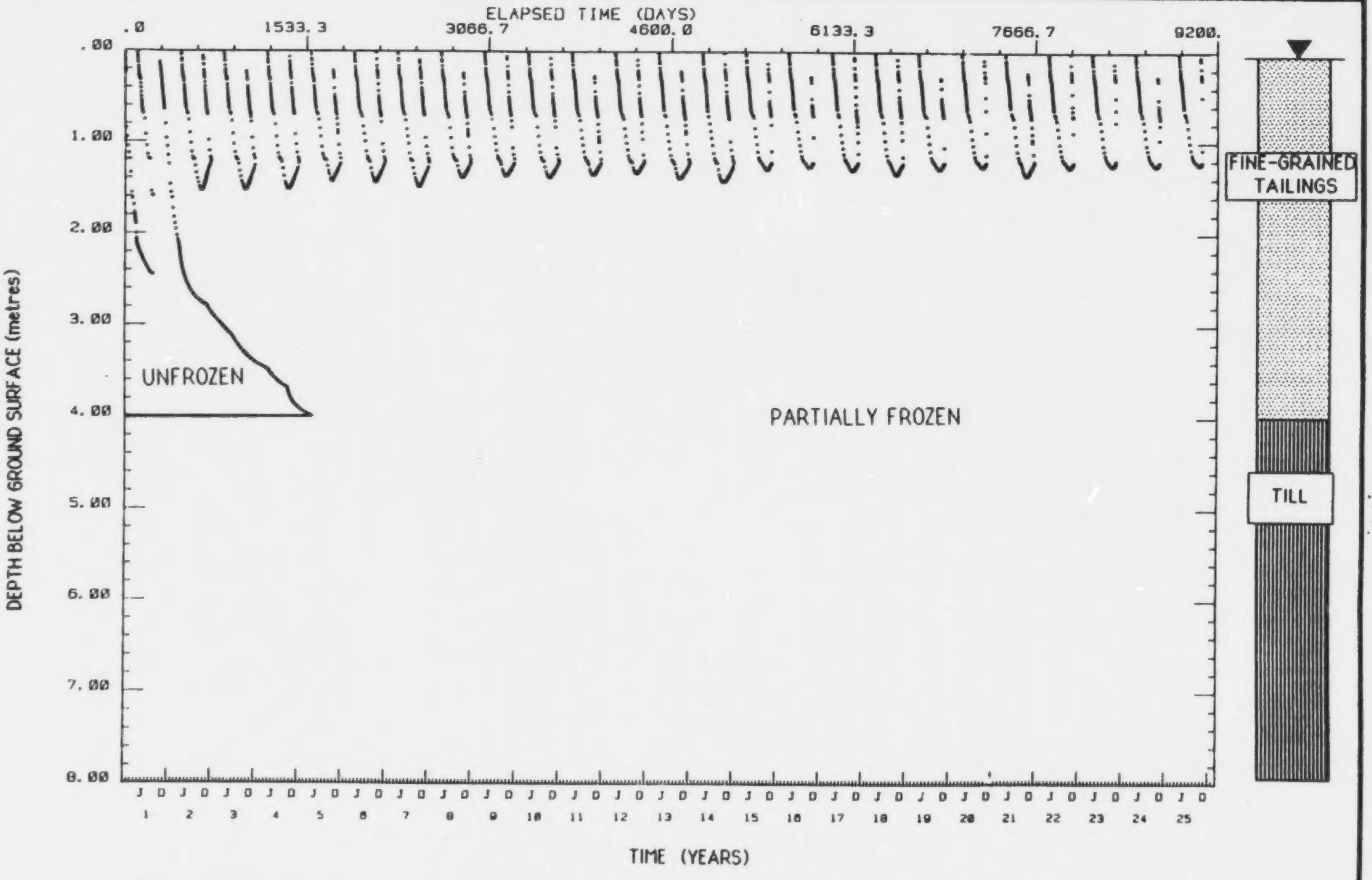


FIGURE 4.6-14 FREEZING ISOTHERM WITH TIME AT KEY LAKE SITE ASSUMING 10 PERCENT OF NORMAL SNOW COVER WITH EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS)

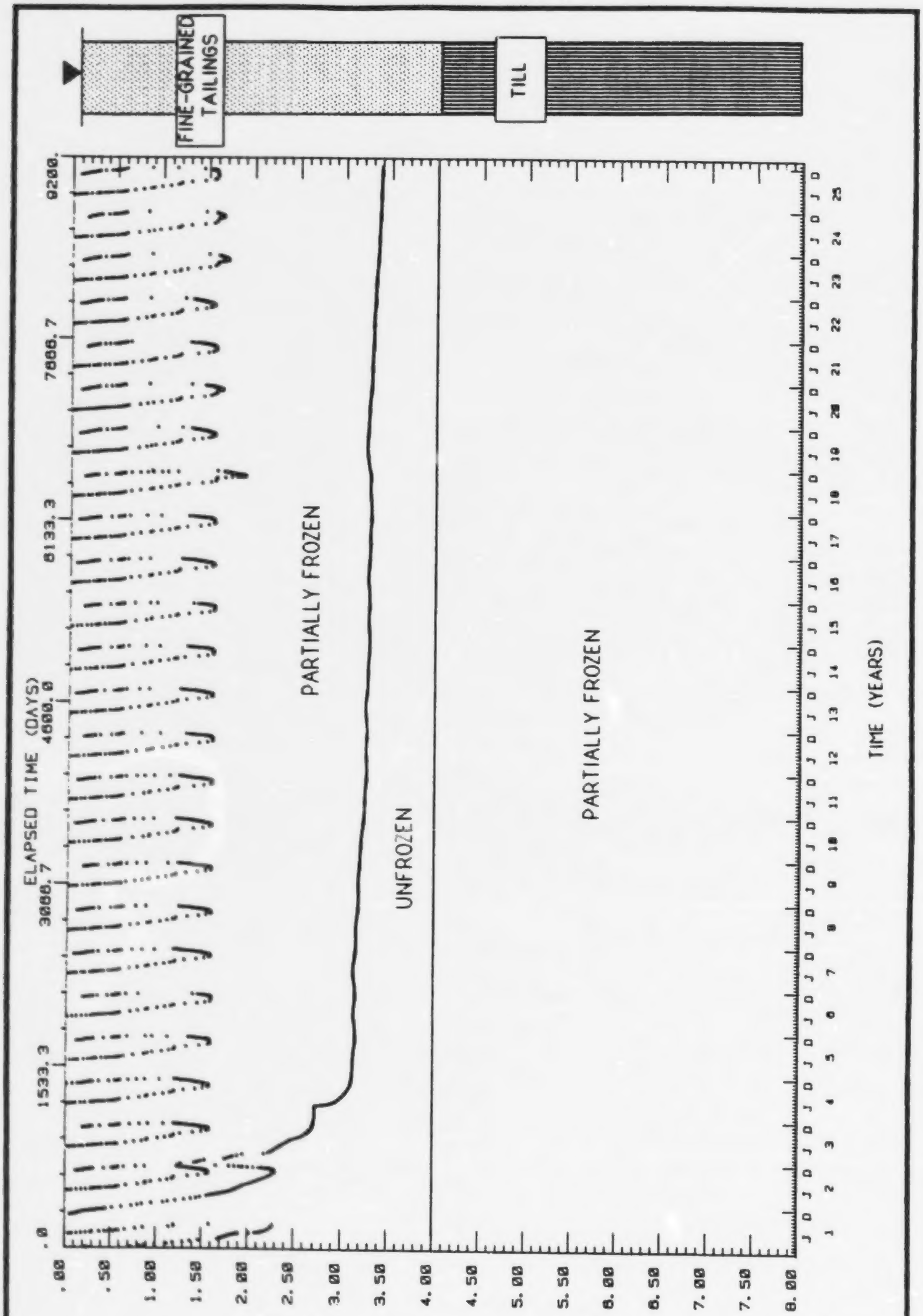


FIGURE 4.6-15 FREEZING ISOTHERM WITH TIME AT KEY LAKE SITE ASSUMING 50 PERCENT OF NORMAL SNOW COVER WITH HIGH EVAPOTRANSPIRATION EFFECT (0 TO 25 YEARS)

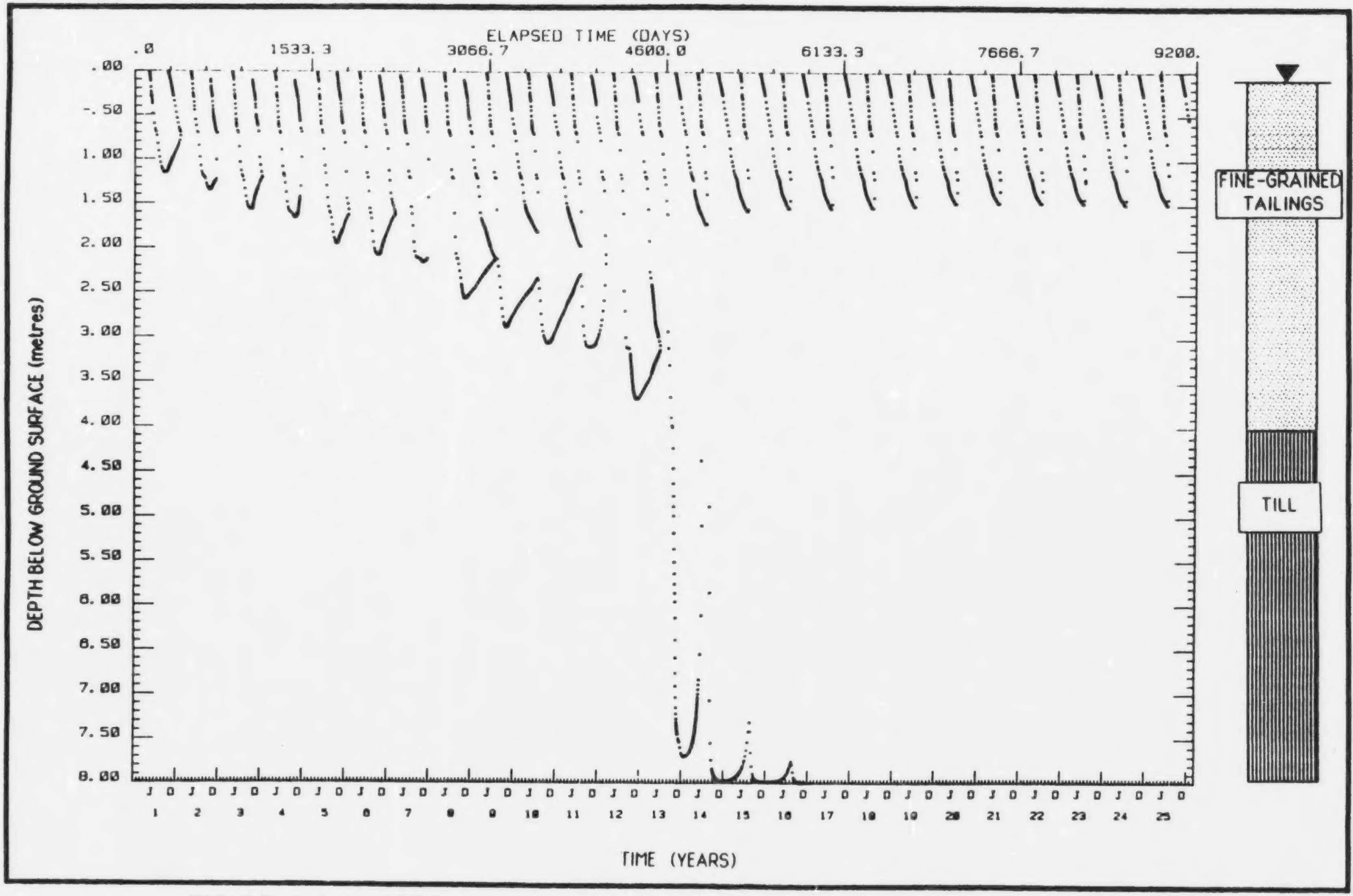


FIGURE 4.6-16 FREEZING ISOTHERM WITH TIME AT KEY LAKE SITE
ASSUMING THAT THE TAILINGS ARE ORIGINALLY FROZEN (-2 C),
NORMAL CLIMATIC CONDITIONS AND LOW
EVAPOTRANSPIRATION EFFECTS
([illegible]D 2[illegible]EAR[illegible])

This analysis shows that permafrost can aggrade until such time as the water table drops enough for the ground surface to dry, even for areas where snow depths average 50% of the monthly means.

Analysis K4 (Figure 4.6-16) used an initial ground temperature of -2°C. For normal climatic conditions and low evapotranspiration effects, the permafrost thaws over a period of 13 years. The average rate of thaw front penetration is 0.2 m per year.

The Key Lake tailings pond is still in operation and is submerged over an appreciable area at various times. Analyses of this condition show that in the short-term, permafrost will aggrade in areas above water, if snow depths are as much as half the normal snow depth and the groundwater is effectively at surface. Otherwise, the tailings will remain unfrozen. Submergence was not simulated; however, the high latent heat associated with ponded water is known to either prevent or dampen any freezing effects. The occurrence of freezing in areas of very shallow water will be dictated by the amount of snow cover. Typically for water depths greater than approximately 1 m, the water will insulate the underlying soils against freezing.

Assuming subsequent drainage of the tailings will lower the water table significantly, it is expected that in the long-term thermal and physical conditions at Key Lake will tend to develop similar to those at Gunnar. The net effect of lowering the water table is to reduce the evapotranspiration to a negligible amount.

4.6.3 RABBIT LAKE

The soil profile used for analysis of the Rabbit Lake tailings site is shown on Figure 2.4-3. Table 4.6-8 summarizes the soil properties used. The profile consists of 20 m of low density fine-grained tailings overlying a 0.5 m thick layer of peat. The peat is underlain by 4.5 m of till, below which is bedrock. The water table is at or close to ground surface. Meteorological conditions are summarized in Table 2.4-1 and the surface thermal properties are summarized in Table 4.6-9.

TABLE 4.6-8

SOIL PROPERTIES
RABBIT LAKE PROFILE

DEPTH INTERVAL (m)	0 - 20	20 - 20.5	20.5 - 25	25 +
MATERIAL DESCRIPTION	Fine Tailings	Peat	Till	Bedrock
Above/below water table	Below	Below	Below	Below
Clay Fraction (%)	4.0	0.0	5.0	0.0
Water Content (%)	85.0	80.0	11.0	5.0
Dry Density (Mg/m^3)	0.83	0.50	2.10	2.20
Freezing Point (°C)	0.44	0.0	0.0	0.0
Quartz Content (%)	38.0	0.0	60.0	75.0
Specific Surface Area (m^2/g)	10.0	-	60.0	0.05
Pore Water Salinity (ppt)	8.0	0.0	0.0	0.0
Thermal Conductivity (W/m°C)				
Frozen	2.18	0.60	3.63	2.75
Unfrozen	0.92	0.38	2.83	2.72
Specific Heat (kJ/kg°C)				
Frozen	1.50	1.98	0.91	0.71
Unfrozen	2.32	2.90	1.08	0.75
Latent Heat at 20°C (MJ/m^3)	234.0	135.0	72.0	37.0

TABLE 4.6-9
SURFACE THERMAL PROPERTIES
RABBIT LAKE SITE

1.	SNOW COVER:	Thermal conductivity	0.31 W/m°C
		Surface emissivity	0.90
		Surface absorptivity	0.50
2.	GROUND SURFACE: (no snow)	Surface emissivity	0.90
		Surface absorptivity	0.75

Four analyses runs were performed for the Rabbit Lake site, corresponding essentially to the analyses for Key Lake. Three of the runs used an initial ground temperature of 0°C.

The analyses are summarized in Table 4.6-10. Analysis R1 (Figure 4.6-17) considers normal climatic conditions and no evapotranspiration. Results show a small net heat gain and a steady seasonal frost depth of about 2.1 m. For analysis R2, the snow cover was reduced to 10 percent of normal, and a small evapotranspiration factor (0.2) was included. The results, presented in Figure 4.6-18, show a net heat loss and permafrost aggradation. Superimposed on the figure are lines representing advance of the freezing front over a 100 year period. Approximately 100 years are required for the freezing front to penetrate the full depth of tailings.

Although the water is at ground surface, no surface evaporation was allowed in the above analyses. These analyses represent a long-term scenario where drainage of the tailings will lower the water table below ground surface. If a high evapotranspiration factor (0.5) is introduced to account for the full heat loss associated with evaporation from a water table at surface, permafrost aggrades into the tailings as shown by analysis R3 (Figure 4.6-19), even with 50 percent snow cover. This latter case is expected to be a short-term condition.

Analysis R4 (Figure 4.6-20) addresses an initially frozen soil profile with a temperature of -2°C. For normal snow conditions and low evapotranspiration, gradual thawing occurs, at an initial rate of approximately 0.1 m per year. This is very close to the borderline between freezing and thawing. More reliable predictions would require site specific calibration of the model.

Rabbit Lake is a recently abandoned site (1985) where groundwater is near surface. The impoundment is still being used for water storage. Analyses of the site show that a high evapotranspiration factor and mean monthly snow depths of up to half the normals will produce permafrost aggradation. Substantial depths of frozen tailings observed at the Rabbit Lake site suggest that these conditions prevail and that the permafrost, for the present time, could continue to aggrade. However, the analyses have also shown that if enough drainage occurs to lower the groundwater table to the point where the ground surface becomes fairly dry, thawing will occur. Assuming this drainage does occur, the ground will thaw in the long-term and if the present surface conditions prevail, physical and thermal conditions will be similar to those observed at the Gunnar site.

An interesting point is that the existing permafrost might be maintained if the impoundment were kept flooded and a high evapotranspiration heat loss maintained in the long-term. This condition, however, may conflict with other decommissioning goals that require a cover to prevent wind and water erosion.

TABLE 4.6-10

SUMMARY OF THERMAL ANALYSES
RABBIT LAKE SITE

ANALYSIS NUMBER	FIGURE NUMBER	TAILINGS PROFILE	INITIAL GROUND TEMPERATURE	WIND SPEED	SNOW DEPTHS	EVAPOTRANS- PIRATION	PREDICTED GEOTHERMAL CONDITIONS	SEASONAL FREEZE/THAW DEPTH (m)	YEARS FOR TAILINGS TO FREEZE (THAW)
R1	4.6-17	Fine	0°C	Normals	Normals	0.0	Seasonal Freezin	21	-
R2	4.6-18	Fine	0°C	Normals	10 percent	0.2	Aggrading Permafrost Seasonal Thawing	1.5	100
R3	4.6-19	Fine	0°C	Normals	50 percent	0.5	Aggrading Permafrost/ Seasonal Thawing	1.5	<100
R4	4.6-20	Fine	-2°C	Normals	Normals	0.0	Gradual Increase in Active Layer Thickness	3-4	

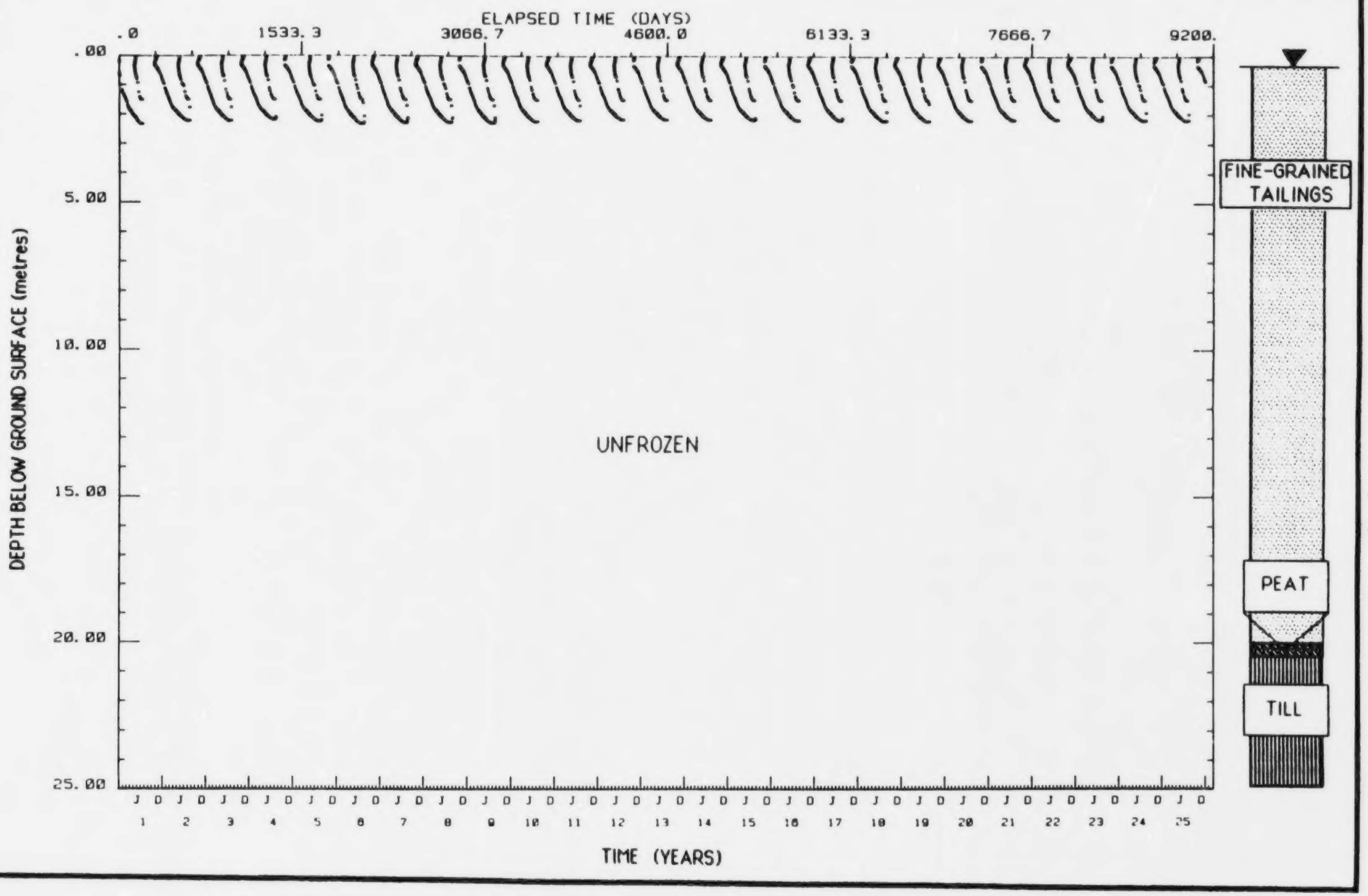


FIGURE 4.6-17 FREEZING ISOTHERM WITH TIME AT RABBIT LAKE SITE ASSUMING NORMAL CLIMATIC CONDITIONS AND NO EVAPOTRANSPIRATION EFFECTS (0 TO 25 YEARS)

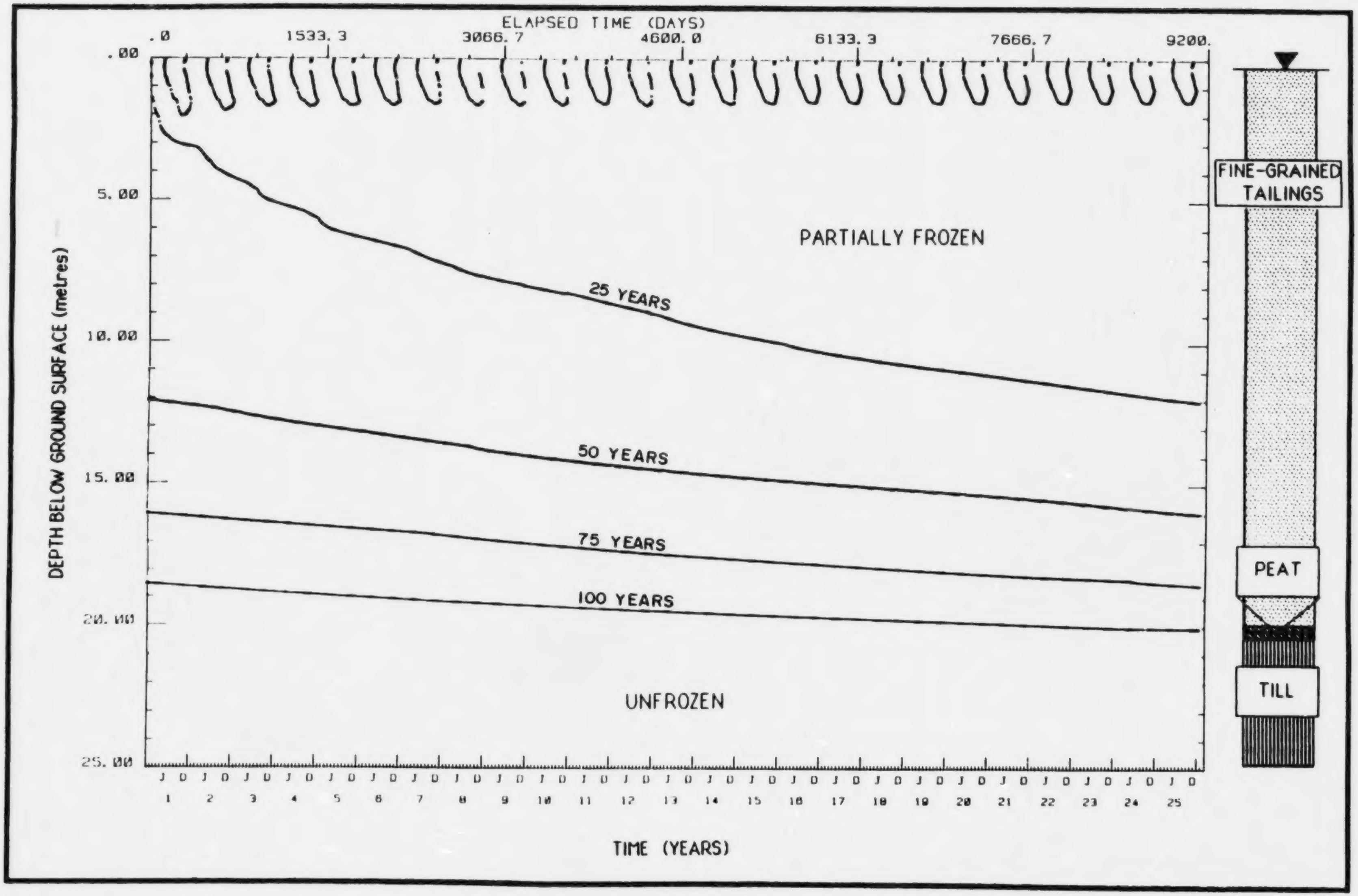


FIGURE 4.6-18 FREEZING ISOTHERM WITH TIME AT RABBIT LAKE SITE
ASSUMING 10 PERCENT OF NORMAL SNOW COVER
WITH EVAPOTRANSPIRATION EFFECTS
(0 TO 100 YEARS)

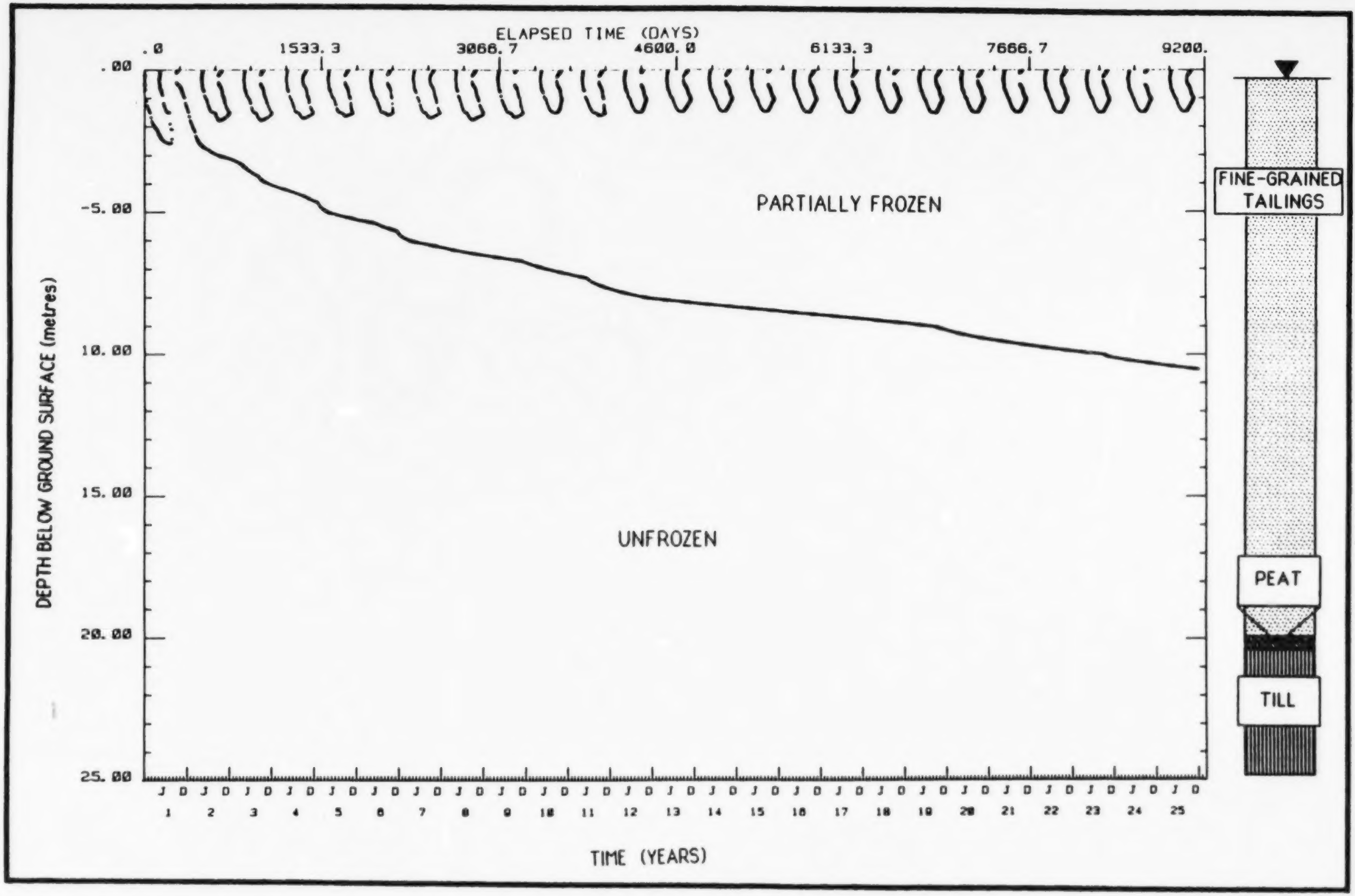


FIGURE 4.6-19 FREEZING ISOTHERM WITH TIME AT RABBIT LAKE SITE ASSUMING 50 PERCENT OF NORMAL SNOW COVER WITH HIGH EVAPOTRANSPIRATION EFFECT (0 TO 25 YEARS)

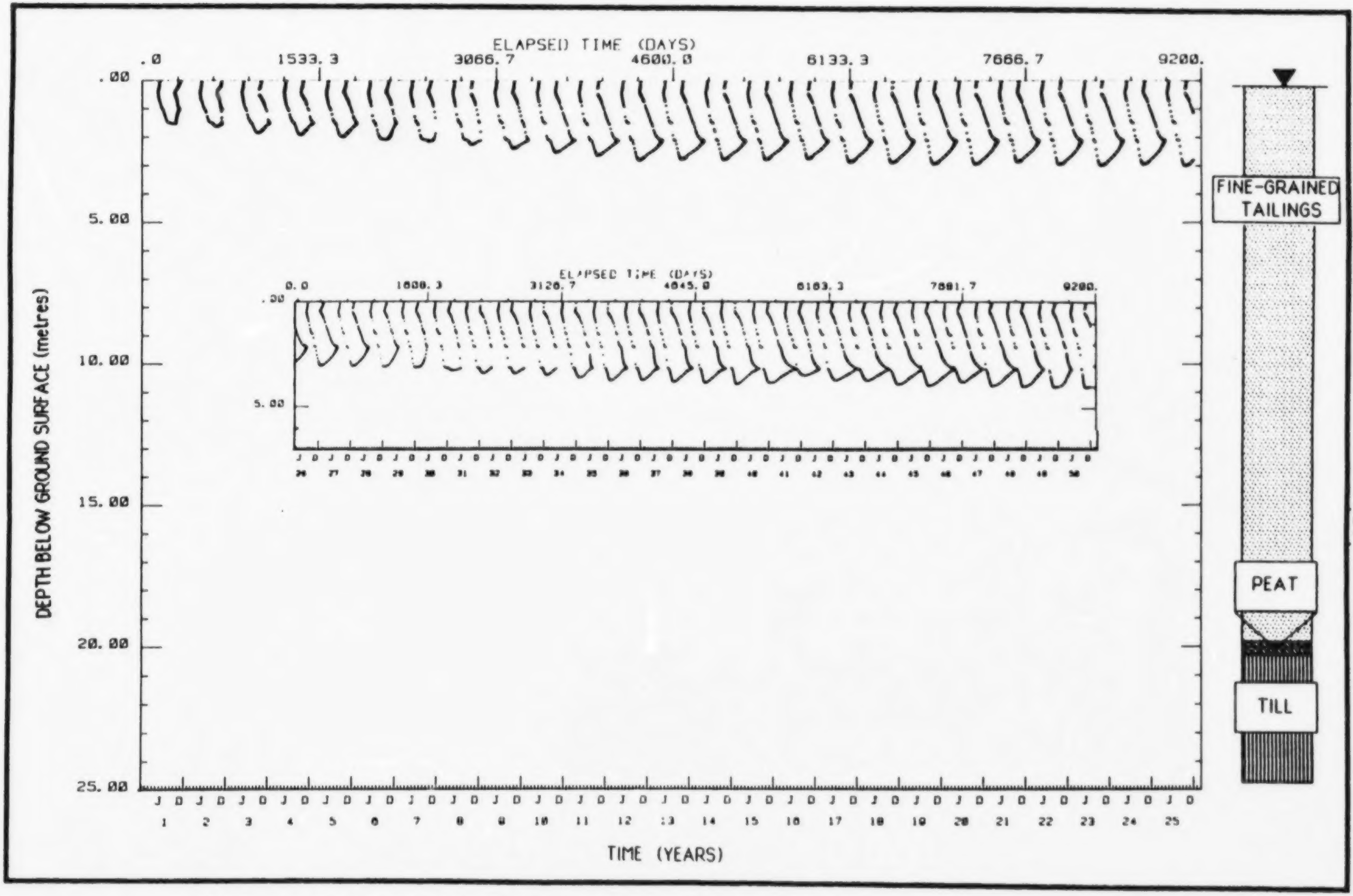


FIGURE 4.6-20 FREEZING ISOTHERM WITH TIME AT RABBIT LAKE SITE
ASSUMING THAT THE TAILINGS ARE ORIGINALLY FROZEN (-2 C),
NORMAL CLIMATIC CONDITIONS AND LOW
EVAPOTRANSPIRATION EFFECTS
(0 TO 25 YEARS)

CHAPTER 5.0
THAW CONSOLIDATION

5.1 GENERAL

One of the decommissioning measures being considered for abandonment of a tailings facility is the placement of a granular surface drainage blanket capped with a low-permeability soil cover. The long-term integrity of such a cover is crucial to the adequacy of the decommissioning. Where surface and climatic conditions promote thawing, the presence of permafrost in the tailings will cause surface settlements to occur. Conversely where freezing conditions are promoted there is potential for frost heave. Local variability of surface conditions and soil texture can result in irregular surface heave and settlement distributions. Therefore the desired surface drainage patterns may not be achieved until the thermal and pore pressure regime has come to equilibrium for the final surface and climatic conditions.

In cases where the soil is relatively permeable and thawing occurs slowly, excess water will flow from the soil at a similar rate at which it is produced. Only if thawing occurs rapidly, or if drainage is impeded, will excess pore pressures develop that can lead to strength loss and instability.

Detailed assessment of the rate and magnitude of thaw consolidation requires a fully coupled thermal and consolidation analysis that considers the effect of a moving boundary in the conduction formulation (Hwang 1976). A simplified means of estimating the rate of thaw consolidation is the Morgenstern and Nixon (1971) approach, which combines Terzaghi's linear theory of consolidation with a classical solution for heat conduction.

The degree of consolidation during thaw is a function of the Thaw Consolidation Ratio, R, which is defined as:

$$R = \frac{\alpha}{2c_v^{0.5}}$$

where c_v is the coefficient of consolidation and α is the constant in the expression relating depth of thaw, χ, with time, t:

$$\chi = \alpha(t)^{0.5}$$

The above expression for thaw depth does not necessarily produce the same form of relationship for thaw depth versus time as predicted in the thermal analyses of the thawing profiles presented in the previous section. Thus some approximate curve fitting is required in order to estimate the value of α for determination of the thaw consolidation ratio.

5.2 ESTIMATED RATE AND MAGNITUDE OF THAW SETTLEMENT

As noted above, excess pore pressures are most likely to develop under conditions of rapid thaw and/or impeded drainage. The maximum rate of thawing predicted from the thermal analysis of ice-rich tailings is approximately 0.5 m per year for the Gunnar site. For a coefficient of consolidation of 50 m^2/year, based on properties of the very fine-grained tailings at Key Lake, it is estimated that between 92 and 98 percent of the excess pore pressures generated by thawing will dissipate as thawing progresses. For the given soil parameters this rate of dissipation is probably conservative since it is based on one-dimensional consolidation. Due to the localized nature of the ice-rich areas, three-dimensional effects will likely increase the rate of consolidation.

Magnitudes of the settlement that accompany consolidation are dictated by the amount of excess ice.

Based on the descriptions of ice content given in the Gunnar borehole logs (BBT 1986) it is thought that settlements in the order of 1 m could be expected at the centre of the mounds, a value that corresponds to the height of the mounds. This estimate is reasonable since the mounds are attributed to frost heave. If a 1 m veneer of soil cover were placed and levelled at Gunnar and snow depths approached normal values, it would be expected that thawing of ice rich materials below the active layer, and hence settlements, would occur within a period of between 15 and 25 years.

Approximately 15 m of frozen tailings were encountered near the north dam at Rabbit Lake. The moisture content and gradations for the frozen and unfrozen tailings are compared in Section 2.4.5 (Table 2.4-3).

The average moisture content of the frozen tailings is 93% and the specific gravity is 2.56. Assuming fully saturated conditions and ice density of 0.9, the frozen void ratio is approximately 2.6. The average moisture content of the thawed tailings is 66% and the resulting void ratio is 1.68. Should the frozen tailings thaw, it is reasonable that the void ratio would, with time, reduce to the void ratio characteristic of thawed tailings. The resulting settlement is 25% or 3.5 m over a 15 m tailings thickness.

The predicted rate of thaw for the Rabbit Lake tailings is very slow and consists of a gradual increase in active layer thickness.

The coefficient of consolidation determined from oedometer tests on the Rabbit Lake tailings ranges from 0.2 to 1.0 m^2/day (73 to 365 m^2/year). The rate of thaw of the permafrost is very slow (2 m in 58 years) for an average of 0.26 m(year)$^{0.5}$. The thaw consolidation ratio R is about 0.015. Therefore, no excess pore water pressures would be developed. Settlement would be governed by the rate of thaw.

Therefore at Rabbit Lake, the existing permafrost would be expected to thaw very slowly with an ultimate surface settlement approaching 3.5 m.

This assumes full surface drainage of the tailings and no evapotranspiration. The effect of a conventional cover would be to accelerate the rate of thaw.

CHAPTER 6.0
FROST ACTION

6.1 GENERAL

Heave of the tailings during seasonal freezing is of concern because:

- Heave could distort the tailings surface and disrupt the surface drainage.
- Potential exists for successive freeze-thaw cycles to transport pore fluid to the surface.

Heave features have been observed at Gunnar and Key Lake that are large enough to disrupt a decommissioned drainage surface. The frost pumping scenario is speculative, but because of the potential for mass transport of fluid from depth to surface, it requires assessment.

This section discusses the technology available for frost heave prediction, presents estimates of heave and estimates of potential fluid pumping. The significance of the heave process is discussed. The frost features observed at Gunnar and Key Lake are discussed in terms of frost heave effects.

6.2 AVAILABLE TECHNOLOGY

6.2.1 GENERAL

There are two fluid transport mechanisms resulting from frost action:

- Frost heave process whereby freezing attracts water towards the freezing front.
- Pore water expulsion whereby water is expelled from the freezing front.

The first process is discussed under segregational heave and the second process under pore water expulsion.

6.2.2 SEGREGATIONAL HEAVE

6.2.2.1 Physics

Frost heave has been a concern for many years in civil engineering applications such as roadways and structures. In the last 15 years, it has been the subject of considerable research with respect to chilled gas pipeline design.

Frost heave is the accumulation of moisture as ice at the freezing front during soil freezing. The conditions necessary for frost heave to occur are:

- Freezing temperatures.
- Available moisture.
- Frost susceptible soil.

Frost heaving consists of two processes:

- Freezing of in situ moisture which results in a 9 percent volume expansion of the pore water.
- Freezing of free moisture which migrates to the freezing front and forms ice lenses.

The heave associated with ice lensing can be considerably more than that associated with in situ moisture freezing.

As the freezing front advances into a frost susceptible soil, suction pressures in the water phase are developed. The suction pressures draw free water toward the freezing front where it freezes into ice lenses and results in volume expansion or heave of the soil. The direction of heave is always parallel to the direction of heave flow. The water phase suction is developed by capillarity action much the same way as capillarity in unfrozen, unsaturated soils. The pressure difference between the ice and water phases is given by:

$$p_i - p_w = 2\,\sigma_{iw}/r_i$$

where p_i = ice pressure (equal overburden pressure)
p_w = water pressure
σ_{iw} = ice-water interfacial tension
r_i = the radius of curvature of the ice water interface

The ice water interface radius is determined by the pore size of the soil. Therefore, a finer grained soil will develop higher suction pressures (p_i-p_w). Typical values of (p_i-p_w) from Williams (1967) are shown in Table 6.2-1.

TABLE 6.2-1
TYPICAL FREEZING SUCTION VALUES

SOIL TYPE	FREEZING SUCTION (kPa)
Coarse sands or coarser	0
Medium and fine sands or coarser silty sands	0-7.5
Medium silt or mixed soils with small amounts >0.006 mm	7.5-15
Largely fine silt or silt with some clay	15-50
Silty clay	50-200
Clay	>200

The heaving process is therefore a coupled thermal and hydraulic process (EBA 1979). Heave is limited both by the thermal capacity to freeze the soil (heat flux) and by the availability of water at the freezing front (fluid flux). It is the coupling of the heat and moisture flow processes that results in the rhythmic ice lensing, or formation of a series of ice lenses within a freezing soil. When the availability of water exceeds the heat removal rate, an ice lense continues to form at the freezing front. When the heat removal rate temporarily exceeds the availability of water, the freezing plane advances to a position where the supply of water is more favorable. The process repeated provides a series of frozen soil and ice lenses.

The water supplied to the freezing front can come from two sources:

- Reservoir at depth.
- Consolidation of soil adjacent to the freezing front.

The intervening soil layers can thus be overconsolidated by the freezing process. In this case, much of the excess water may be readsorbed by the soil upon subsequent thaw.

Considerable work has been done over the years in empirically determining which soils are frost susceptible. The most common criteria is based upon gradation. The U.S. Corps of Engineers Frost Susceptibility Criteria is shown in Table 6.2-2. This table is based upon work by Casagrande (1932). In general, the finer grained soil (expressed as % finer than 0.02 mm) is more frost susceptible. Group F1 is the least susceptible and group F4 the most susceptible.

TABLE 6.2-2
U.S. CORPS OF ENGINEERS
FROST DESIGN SOIL CLASSIFICATION

FROST GROUP	SOIL TYPE	PERCENTAGE FINER THAN 0.02 mm BY WEIGHT	TYPICAL SOIL TYPES - UNIFIED SOIL CLASSIFICATION SYSTEM
F1	Gravelly soils	3 to 10	GW, GP, GW-GM, GP-GM
F2	a) Gravelly soils	10 to 20	GM. GW-GM, GP-GM
	b) Sands	3 to 15	SW, SP, SM, SW-SM, SP-SM
F3	a) Gravelly soils	>20	GM, GC
	b) Sands, except very fine silty sands	>15	SM, SC
	c) Clays, PI >12	-	CL, CH
F4	a) Very fine silty sands	>15	SM
	b) All silts	-	ML, MH
	c) Clays, PI <12	-	CL, CL-ML
	d) Varved clays and other fine-grained, banded sediments	-	CL and ML CL, ML, and SM; CL, CH, and ML; CL, CH, ML, and SM

In uranium tailings, all the conditions necessary for frost heave are present. First, as described in Chapter 4.0, freezing temperatures for a considerable depth are present. Secondly, ample water is available. The water table in tailings deposits is near surface and, even in the underdrained case of Key Lake, the moisture content of the tailings is sufficiently high so as to provide water for heaving. Thirdly, the tailings are sufficiently fine to be frost susceptible (Table 6.2-2).

Predicting the amount of heave is more difficult than predicting whether frost heaving conditions are present. This problem was tackled in the design of chilled gas pipelines in the late 1970's. Two predictive methods arose from this work:

- Hwang (EBA 1979).
- Konrad-Morgenstern (1980, 1981, 1982a and 1982b).

Both approaches recognize the effect of:

- Heat flux or temperature gradient.
- Overburden pressure.
- Pore water pressures upon the rate of heave.

6.2.2.1 Hwang Method

In the Hwang approach, the thermal and hydraulic processes are decoupled. The technology for predicting heat flow with freezing front progression (Chapter 4.0) is well-developed. On the other hand, the techniques for estimating the suction pressures and permeability of the soil required to estimate the fluid flow component are not well developed and confidence in these values to more accuracy than one order of magnitude is rare. The Hwang approach is to carry out a thermal analysis of the problem and obtain the rate of freezing and overburden pressures at the frost front. Samples are then tested in a frost cell (described in Section 6.2.4) at the estimated overburden pressure and rate of heat extraction. The heave or ice segregation ratio (percent of segregated ice) is then applied directly to the frost depth to obtain the estimated heave. Based upon results from the Calgary test site, this method slightly overpredicts the amount of heave. The Calgary test site is described in EBA (1979). It consists of several segments of large diameter pipeline chilled with cooled air. Extensive heave, pore pressure and temperature instrumentation was installed around the pipes. The facility was operated for several years and the amount of heave and frost penetration was observed.

6.2.2.2 Konrad-Morgenstern Method

The Konrad-Morgenstern approach is more rigorous than the Hwang approach. They found that the water intake flux to the freezing front is determined by:

$$v(t) = SP \operatorname{grad} T(t)$$

where: $v(t)$ = water intake flux
SP = segregation potential
$T(t)$ = temperature at the freezing front

The segregation potential is determined from laboratory frost heave oedometer tests and is a function of the suction pressure at the freezing front, the rate of cooling at the freezing front and the overburden pressure. This relationship is illustrated for Devon silt on Figure 6.2-1. The segregation potential can be related to the overburden pressure when the rate of cooling is close to zero and suction is zero by:

$$SP = SP_o \, e^{aPe}$$

where: SP_o = segregation potential at zero overburden pressure
a = soil constant
Pe = stress at the freezing front

For frost heave predictions, the temperature gradient at the freezing front versus time is estimated from a thermal analysis. The external pressure at the freezing front is estimated from the depth of frost and applied surcharge. The water intake flux at any time is estimated with the above relationship and total heave versus time determined by summing the heave for various time steps.

Konrad and Morgenstern (1984) applied this theory to prediction of heave at the Calgary chilled pipeline test site. Good correlation between measured and predicted heave was found.

6.2.2.3 Summary

Both methods of frost heave prediction require a credible thermal analysis to predict temperature distributions and gradients. Both methods use a similar frost heave test to generate soil parameters. The Hwang method is more intuitive and it takes the amount of heave (ice segregation ratio) directly from the test and applies it to the problem at hand. In the Konrad Morgenstern method, a rate of heaving (expressed in terms of water uptake) is derived from the test.

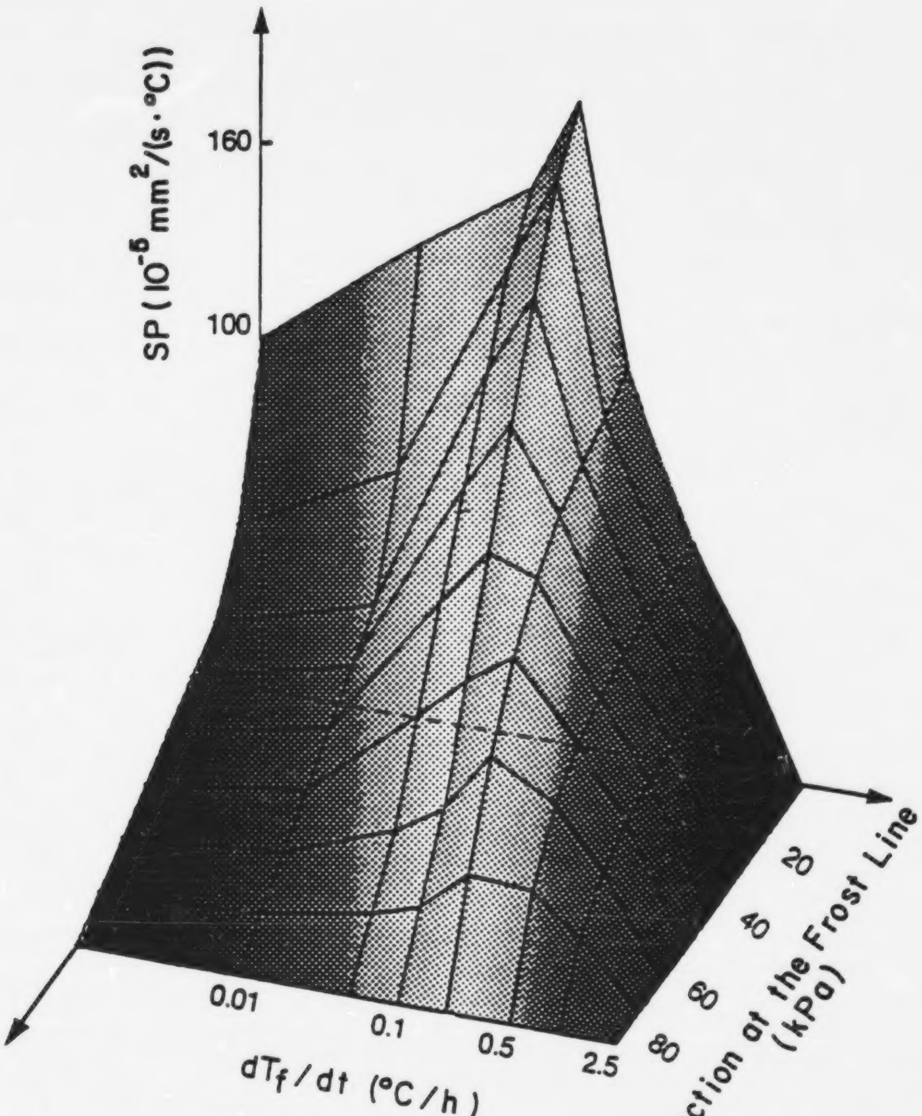


Figure 6.2-1 Characteristic Frost Heave Surface for Devon Silt Used for Simulation

6.2.3 PORE WATER EXPULSION

Freezing can also expel water from the freezing front. This phenomenon has been described by Tsytovich (1975), MacRoberts and Morgenstern (1975) and Arvidson and Morgenstern (1977). The implications of this mechanism to uranium tailings is that the excess pore water pressures generated by freezing can locally rupture the ground surface and form frozen mounds or boils. This process is similar to that accepted for the genesis of pingos in the McKenzie River Delta area (Andersland and Anderson 1978).

Pore water expulsion from a freezing soil occurs when:

- Total stress at the freezing front is high.
- Rate of freezing is high.
- Coarse-grained soils are present.

When the propensity for moisture attraction at the freezing front (Section 6.2.2) is overcome by any or a combination of the above factors, the volume change on freezing forces unfrozen moisture away from the freezing front. Although the occurrence and physics of this phenomenon have been well documented, there is little information available on when pore water expulsion can be expected to occur. The influence of grain size and effective stress are illustrated by Arvidson and Morgenstern (1977). Figure 6.2-2 shows the pore water flow resulting from open system freezing of three soils. For the coarse grained Ottawa sand, pore water expulsion occurred for all affected stresses. For the Devon silt, and modified Devon silt (modified Devon silt has a higher silt content), pore water expulsion occurred at applied stresses greater than 70 and 215 kPa respectively. The pressure above which pore water expulsion occurs is termed the shut-off pressure.

The effect of freezing rate can be seen in the characteristic frost heave surface for Devon silt presented by Konrad and Morgenstern (Figure 6.2-1). The segregation potential, SP, which is representative of the rate of moisture flow to the freezing front becomes zero for a rate of cooling greater than 2.5°C per hour. Presumably, pore water expulsion would occur for larger cooling rates. This rate is, however, extremely large and would not be experienced in natural freezing systems.

Based upon gradational, freezing rate and effective stress criteria, it would appear that pore water expulsion will not occur in uranium tailings. The shut-off pressure for Devon silt, which has a similar gradation to uranium tailings, is 70 kPa or greater. This corresponds to 4 m or more of overburden. As the seasonal frost front does not penetrate to this depth, conditions where the shut-off pressure is exceeded by the effective stress at the frost front are not anticipated. In addition, the rate of cooling under natural conditions is much less than required for pore water expulsion.

Testing reported in the literature was carried out on soils with a moisture content corresponding to a liquidity index of less than 0.5. The tailings have very high moisture contents. It is not clear what effect the initial moisture content has upon frost effects.

6.2.4 DATA REQUIREMENTS

Frost heave characterization will require laboratory tests on actual tailings deposits. The laboratory testing equipment consists of a frost cell which can freeze the sample under control temperature, drainage and stress conditions. Such equipment is described by EBA (1979). It is similar to an oedometer. It consists of an insulated cell into which a cylindrical sample is placed. The sample is frozen from the bottom up. Drainage is provided through a porous stone within the loading cap. The effective stress on the loading cap can be varied. The rate of frost penetration is monitored by a series of thermisters embedded within the cell wall. The displacement of the loading cap during freezing is

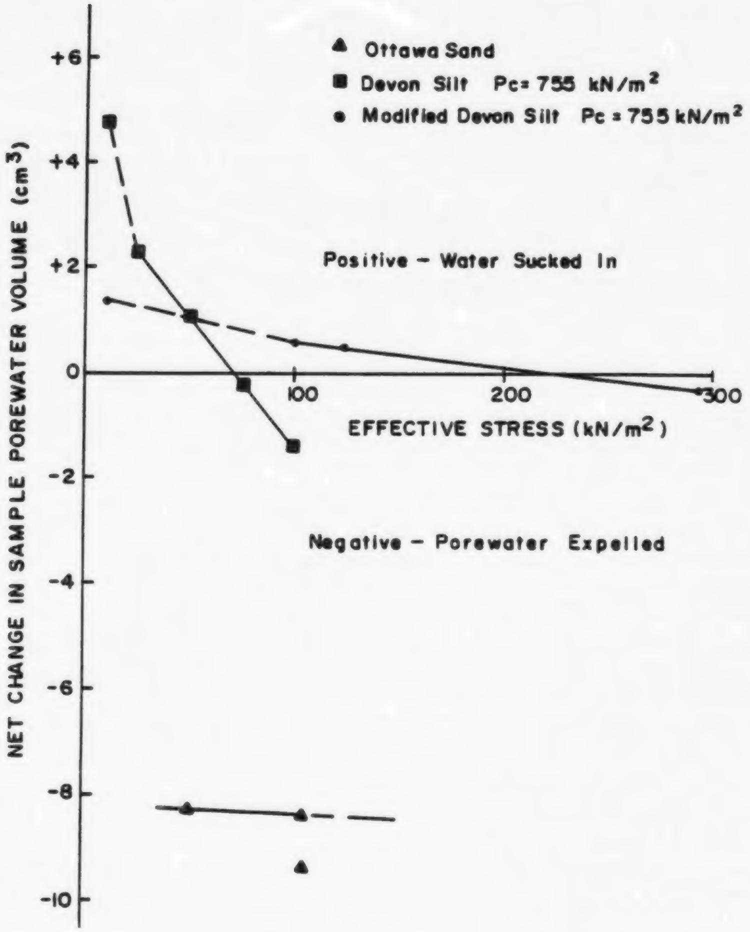


Figure 6.2-2 Net Change in Sample Porewater Volume - Soil Type

recorded. Data obtained from the test includes the frost rate penetration, water volume change (attracted or expelled) and loading cap displacement (heave). The rate of frost penetration, pore water pressure in the unfrozen soil and effective stress are controlled variables. The heave and water volume change are dependent variables.

Repeated tests on tailing samples under different stress conditions can provide either the frost heave surface for the Konrad-Morgenstern theory, or the ice segregation ratio required for the Hwang theory. The equipment can also evaluate whether pore water expulsion or attraction will occur.

This is the primary data requirement for frost heave estimates. In conjunction with the frost heave data, the necessary data for a detailed thermal analysis is also required (Chapter 4.0).

6.2.5 RELIABILITY

Frost heave prediction is in its infancy. Both methods more or less accurately predicted the observed heave at the Calgary test site. Neither have been used in routine heave predictions for engineering applications. As such, they are both in the developmental stage in terms of use as an engineering tool.

The soils to which the theory has been applied are limited. Much research has been done on Devon silt and on the silt and clay present at the Calgary test site. Although the gradation characteristics of these soils are similar to uranium tailings, the moisture content and mineralogy are substantially different. The effect of the initial moisture content on both the frost heave characteristics and upon the shut-off pressure need to be examined in more detail. Specific laboratory testing and field observations on uranium tailings are required before the frost heave theory can be transferred to uranium tailings with confidence. This would consist of a series of frost cell tests, on-site heave measurements and temperature profile measurements.

6.3 EXAMPLE APPLICATIONS

The potential frost heave was estimated for the Gunnar and Key Lake sites using the Konrad-Morgenstern method. This theory was used because data is more readily available. The heave properties of Devon silt adjusted to reflect observed heaving were used. Comparison of gradation and classification data between the tailings and Devon silt are summarized in Table 6.3-1.

The Devon silt has gradational, plasticity and moisture content characteristics similar to the Gunnar fine tailings. Its gradation is also similar to the other tailings, however, its plasticity and moisture content conditions are substantially different.

The frost heave parameters for Devon silt (Arvidson and Morgenstern 1975) are summarized in Table 6.3-2.

TABLE 6.3-1
CLASSIFICATION PROPERTIES

MATERIAL	MOISTURE CONTENT (%)	PLASTIC LIMIT (%)	LIQUID LIMIT (%)	SILT AND CLAY (%)
Devon Silt	25	22	30	83
Calgary Silt	22	-	-	50
Gunnar coarse tailings	13	NP	NP	25
Gunnar fine tailings	25	NP	NP	55
Key Lake tailings	118	-	-	65
Rabbit Lake tailings	55	50	70	70

*NP = non-plastic

TABLE 6.3-2
FROST HEAVE CHARACTERISTICS

MATERIAL	SPo ($mm^2/sec.°C$)	a (MPa^{-1})
Devon silt	120×10^{-5}	8.95
Calgary silt	230×10^{-5}	9.5

Note: $SP = SP_o e^{aPe}$

The rate of freezing was estimated from the modelling presented in Chapter 4.0. The predicted depth of thaw over the freezing season (identified by mean monthly air temperature) was used to determine α from:

$$\chi = \alpha (t)^{0.5}$$

This equation was then used to estimate the depth of frost versus time. The α value for various cases of seasonal freezing presented in Chapter 4.0 is summarized in Table 6.3-3.

TABLE 6.3-3
FREEZING PARAMETERS

MODEL* RUN	FREEZING PERIOD (days)	AIR STEP TEMP (C)	FROST DEPTH (m)	α ($ms^{1/2}$)	EQUIVALENT STEP TEMP. (0°C)	'n'** VALUE
G1	190	-15.8	2.2	5.43×10^{-4}	7.3	0.46
K1	185	-14.5	1.3	3.25×10^{-4}	6.5	0.45
R1	200	-15.1	2.1	5.05×10^{-4}	13.6	0.90

NOTES:

* From Chapter 4.0
**Backcalculated to yield same frost depth in simple thermal model as in Chapter 4.0.

The temperature gradient was determined by taking the surface temperature equal to the freezing step temperature, and the temperature at the freezing front of 0°C. A linear gradient in the frozen zone was assumed. The temperature gradient at the freezing front could then be estimated knowing the depth of frost at any time. Using Konrad and Morgenstern theory, the intake flux can be determined at any time as above.

The seasonal water intake flux is found by summing the flux over the freezing period. The heave to ice segregation is 1.09 times the seasonal intake flux. The heave due to freezing of the in-situ water is 1.09 times the unfrozen soil porosity. The total heave is the sum of the ice segregational heave plus the in-situ heave. The results of the analyses are shown in Table 6.3-4.

TABLE 6.3-4
ESTIMATED SEASONAL HEAVE SUMMARY

SITE	COVER DEPTH (m)	FROST DEPTH (m)	WATER INTAKE (mm)	SEGREGATED HEAVE (mm)	IN-SITU HEAVE (mm)	TOTAL HEAVE (mm)	ICE SEGRATION RATIO (%)
Gunnar	0	2.2	190	210	80	290	13
	1	2.44	130	140	50	190	
	2	2.83	77	85	30	115	
Key Lake	0	1.3	305	332	90	421	32
	1	1.74	175	190	55	245	
	2	2.30	80	90	25	115	
Rabbit Lake	0	2.1	428	470	130	600	22
	1	2.51	300	325	95	415	
	2	3.0	190	210	60	270	
Gunnar - continuous freezing to 5 m (3 years)							
	0	5	425	460	175	635	12

NOTE: Calibrated to first thermal analysis for each site from Chapter 4.0 (Normal temperature, wind and snow)

- $SP_0 = 2.5 \times 10^{-9}$ $m^2/°C$ sec (twice Devon silt values)

Also investigated were cases with the non-frost susceptible cover at the surface of the tailings. The results of this analysis are also shown in Table 6.3-4. This analysis does not couple the thermal and mass transport directly. However, the amount of segregated ice predicted was not enough to retard the frost front penetration appreciably. Errors resulting from neglecting this coupling will tend to overpredict the heave.

6.4 DISCUSSION

The heave estimates were calibrated with the following observed frost features:

- Gunnar frost boils.
- Key Lake frozen section, photo 2.3-2.
- Key Lake hummocks, photo 2.3-1.

The Gunnar boils are approximately 1 m in height above the surrounding terrain. The frost depth is approximately 5 m for a total heave of approximately 20 percent. The photograph of frozen tailings shows a visible excess ice content of about 30%.

Initial heave estimates were made using Devon silt frost heave parameters. The total heave at the frost boils and the estimated ice segregation ratio for the Key Lake tailings was about one half of that observed in the Key Lake photograph. As a result, the segregation potential was doubled over the Devon silt values for the estimates. The overburden parameter was unchanged.

The results of this estimate are shown in Table 6.3-4. The estimated heave for the Gunnar frost boils is 0.6 m and the ice segregation ratio for Key Lake tailings is 32%, both of which more or less agree with observed conditions.

The potential frost heave at each site has been estimated based upon frost depth and assumed heave properties. Frost features have been observed at the Gunnar site and the Key Lake site. At Gunnar the frost features are boils with a permafrost core to a depth of approximately 5 m, protruding approximately 1 m above the surrounding terrain. The resulting segregated ice content is approximately 1 ÷ 5 = 20%. This is consistent to slightly more than the segregation estimated by the frost heave theory (12%).

The features at Key Lake are a different story. The frost features develop near a standing pool of water on an active tailings deposition face placed during the previous winter. The depositional sequence would be:

- Frozen deposition.
- Thawed deposition.
- Continued deposition.
- Freezing and mounding.

During the second winter in which the features were formed, there would be frozen soil at depth and a surface thawed layer deposited in the previous summer. The relief of the features in June after a minimum amount of thaw could have occurred was estimated by Knight and Piesold (1986), at between 1 and 1.2 m. The surface expression of the hummock is typical of heaving (i.e., extensive cracking on the high parts of the hummock). If the relief had resulted from thaw in the low areas, the major cracking would be on the flanks of the hummocks rather than on the top.

It is difficult to attribute all of the heaving to ice segregation heave alone . The relief is about equal to the predicted frost depth alone (1.4 m). Such features might be formed by pore water expulsion ("pingo process"). Freezing would create excess pore pressures. Water would then flow to a "weak spot" and migrate to the surface. Once at surface, it would freeze, forming the mounds. This freezing always takes place close to the surface; considerably more ice can accumulate in one season than can heave by the ice segregation process.

The problem with this mechanism is that, based upon gradation, the tailings ought not to expel water on freezing. If the features are indeed a result of pore water expulsion, then, either the tailings in this area are considerably more sandy than reported in other areas, or high moisture content tailings develop pore water expulsion characteristics more readily than do the soils tested and reported in the literature. The question cannot be resolved within the scope of this study, and further laboratory testing and field observations would be required to explore the mechanism.

6.5 FROST HEAVE "PUMPING" MECHANISM

Frost pumping is a process whereby successive seasonal freezing can transport fluid from depth to the surface. To our knowledge this process has not been closely studied in the literature or in the field. As such, the mechanism of the process is speculative.

As discussed in the previous section, frost heave can result in significant amounts of water being drawn toward the freezing front. As the soil thaws from the surface, this fluid would be liberated. Downward flow would be blocked by frozen soil and upward flow could occur as the tailings consolidate. As an upper limit, the potential for frost pumping is equal to the amount of segregational heave. The net effect of seasonal freezing would then be to "pump" successively pore water from depth to the surface.

The source of water for segregational heave is not clear. Some undoubtedly comes from free water at depth. Some also comes from consolidation of the soil adjacent to the developing ice lense. If the soil is quite incompressible, flow from depth would be likely. However, if it is compressible, then consolidation of the adjacent soil is likely to happen.

Should flow arise from consolidation of adjacent soils, then upon subsequent thaw, liberated water would be readsorbed by the soil and would not flow towards surface. Should readsorbtion by adjacent soil layers be the dominant mechanism, then frost pumping is unlikely to occur.

Evidence of the pumping action is in part supported by the freeze consolidation tests conducted by Knight and Piesold (1986). They exposed cylinders of tailings to freeze-thaw cycles and compared the rate of fluid-solid separation of the freeze-cycled tailings to tailings that had been allowed to consolidate under nonfreezing situations. Freezing and thawing increased the density of the tailings by approximately 50% over the density of settled tailings. The freezing process was closed, i.e., access to free water during freezing was not allowed, as would be the case in naturally frozen tailings. However, the indication is that not all of the water is readsorbed in the tailings soil mass upon thaw.

Further work would be required to assess whether the frost action is a significant mechanism for mass transport of tailings fluid to the surface. One potential technique would be to install moisture-density tubes in the tailings and obtain detailed moisture content profiles at the end of freezing and during subsequent thaw. A net decrease in moisture content of the thawed soil during the thawing process would indicate fluid flow towards the surface.

CHAPTER 7.0
SOIL PARTICLE TRANSPORT

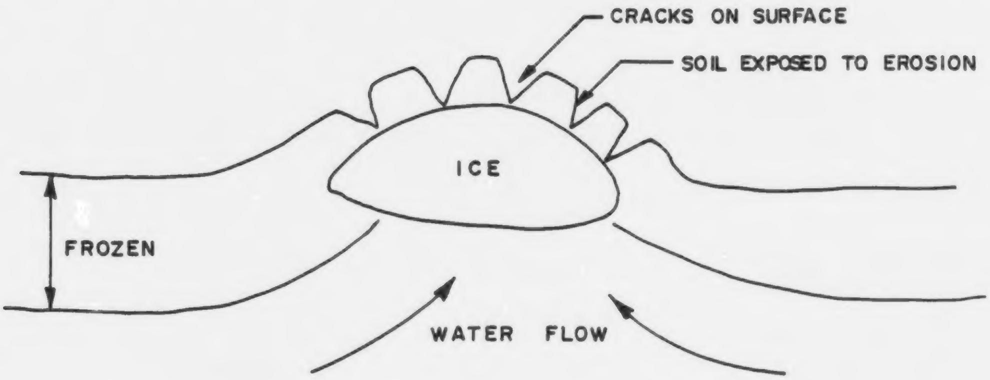
Frost action may result in soil particle transport in two ways. Firstly, frost features can expose surface soil to increased air and water erosion. Secondly, frost action can transport soil particles directly to the surface; however, this mechanism is not believed to be significant in uniform grained tailings deposits.

Frost features that increased soil exposure to wind erosion have been observed at Gunnar and Key Lake tailings deposits.

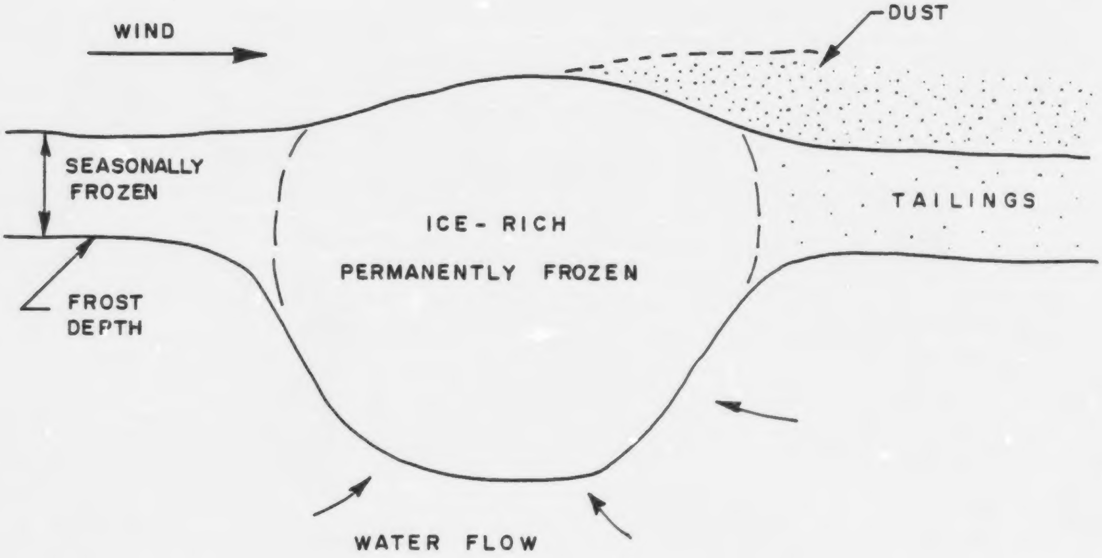
At Key Lake, frost features up to 1.2 m in relief have been observed (Knight and Piesold 1986). As discussed in Section 6.0, these features probably result from pore water expulsion and mounding where the expelled water escapes to the surface. The relief results in cracking of the soil in tension above the mound and exposes it to wind and other forms of erosion. This process is illustrated in Figure 7.0-1. Erosion resistant covers would limit soil particle transport. Sufficient thickness would be required so that the cover remains intact after heave. As illustrated in Section 6.0, the cover will have less effect on controlling the amount of heave for expulsion heaving than in ice segregational heaving.

Frost heave has also resulted in soil particle transport at the Gunnar site. Here, cracking of the soils did not occur, however, wind erosion from the surface of the mounds increased. The frost mounds developed as discussed in Sections 4.0 and 6.0. The surface of the mounds is exposed to a greater degree than the surrounding tailings surface. The exposed surface is more susceptible to wind erosion. BBT (1986) observed wind erosion that was reflected in an obvious dust plume over a recent snow cover. Very modest erosion resistant covers would provide control of this type of soil particle transport.

Frost action can also result in the transport of large (i.e., boulder particles) through a fine-grained soil matrix. In prairie till landforms, which contain numerous boulders within a silty clay matrix, this mechanism results in the continued transport of cobbles and boulders to the ground surface. Similarly in many northern permafrost regions "patterned ground" occurs, where cobbles and boulders have been sorted into circles, polygons steps or stripes, see Washburn (1956) for the classic description. As the tailings deposits are of uniform gradation, this mechanism is not considered to be significant in uranium tailings, except in regard to the behaviour of rockfill or gravel covers.


CRACKS ON SURFACE
SOIL EXPOSED TO EROSION
ICE
FROZEN
WATER FLOW

KEY LAKE – FROST BOILS


WIND
DUST
SEASONALLY FROZEN
ICE-RICH
PERMANENTLY FROZEN
TAILINGS
FROST DEPTH
WATER FLOW

GUNNAR – FROST BOILS

Figure 7.0-1 Frost Boils - Key Lake and Gunnar

CHAPTER 8.0
EFFECT ON PERMEABILITY

8.1 GENERAL

Repeated freezing and thawing can affect the permeability of tailings and cover soils. Freezing forms a secondary structure within the soil and increases the permeability.

8.2 TAILINGS

Freezing of tailings will result in some ice segregation. Locally, thin layers of tailings will become overconsolidated as a result of freezing suction pressures. Horizontal ice lenses will form between the soil layers. Upon thaw, the soil may reabsorb some of the fluid, however the discontinuities between the soil layers will remain. These discontinuities will result in increased permeability, primarily in the horizontal direction.

Knight and Piesold (1986) observed a frost induced structure and presented photographs showing finely fissured tailings structure after thaw.

Little information exists on quantifying the increase in permeability. Typically, in natural soils in Saskatchewan, a difference of one to two orders of magnitude exists between weathered (subject to freeze-thaw) and unweathered soils of similar composition. The change in permeability is clearly a result of secondary structure. Some of this difference is attributable to freeze-thaw action and some to surficial desiccation.

The permeability of the tailings is of interest, since it controls the drainage capability and rate of consolidation of the tailings. Since frost action will tend to increase the permeability more in a horizontal direction, and consolidation drainage will occur primarily in a vertical direction, it would be prudent to allow only a minimal increase in permeability when estimating drainage rates. If frost pumping (Section 6.0) occurs, this would also tend to consolidate the upper zone of tailings. However, this process should be treated in isolation from the change in tailings permeability.

8.3 COVERS

Frost action effects on covers will be through a slightly different mechanism. The covers are at a considerably lower moisture content than the tailings. Secondary structure from frost heave will be much less of a factor. A second method of secondary structure formation exists in low moisture content soils. Frost shrinkage has been studied with respect to highway subgrades by Hamilton (1966). Volume shrinkage of up to 3 % was observed in unsaturated compacted clay till samples as illustrated in Figure 8.3-1. The shrinkage results in vertical cracking. The crack structure would significantly increase the vertical permeability of the cover soil.

Information on the magnitude of permeability increase is not available and further field investigation is required if the cover design is to allow for the barrier to freeze. A reduction of one order of magnitude from the laboratory values to field values would not be unreasonable.

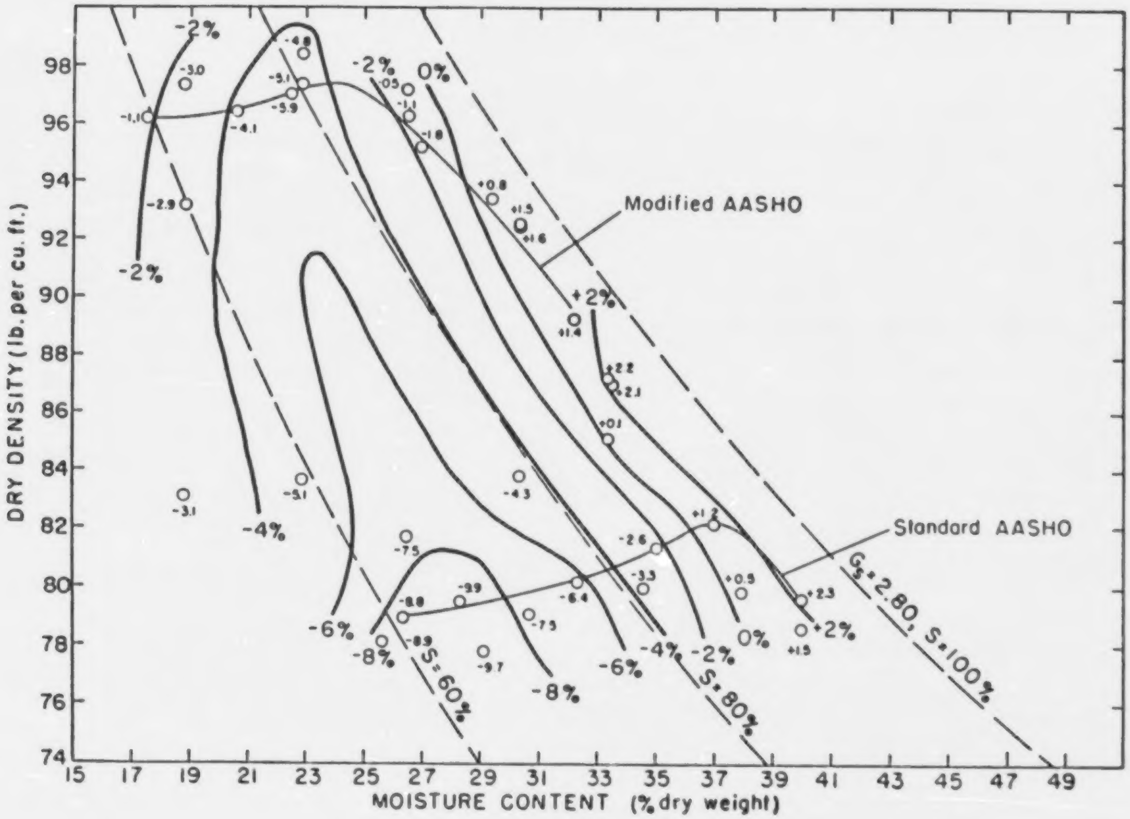


Figure 8.3-1 Relationship Between Density, Moisture Content, and Freezing Volume Change for TH Clay. Freezing Temperature - 20°F (after Hamilton, 1966)

CHAPTER 9.0
REVIEW OF FROST CONSIDERATIONS IN DECOMMISSIONING DESIGN

9.1 FROST CONSIDERATIONS IN DECOMMISSIONING DESIGN

9.1.1 GENERAL

Alternative cover designs are shown in Figure 3.1-1. They consist of:

- Rock/gravel cap.
- Vegetation only.
- Engineered cap with rock cover.
- Engineered cap with vegetated cover.

This section assesses the effect of frost on each of these structures. Methods of promoting permafrost aggradation are also assessed.

The objectives of the decommissioning covers are to:

- Limit infiltration into the tailings mass, by barriers and by promotion of surface runoff.
- Prevent erosion and transport of tailings particles.
- Limit direct radioactive release.

The effect of frost upon the first two objectives are discussed.

The primary effect of frost action upon the cover is surface displacement and its effect upon surface drainage. The covers would be graded to promote runoff. Disruption in surface drainage could result in ponded runoff and increased infiltration. Surface displacement can result from thaw settlement associated with included ice, or from direct heave of the cover, either from segregational or pore water expulsion heaving.

The engineered barriers rely upon a soil barrier layer with an assumed permeability of 10^{-9} m/s to limit infiltration. The influence of frost upon barrier permeability is a concern.

The expulsion heave features observed at Key Lake resulted in major cracking of the soil. In the thin cover cases this would result in exposure of the tailings to wind and water erosion. Maintenance or development of permafrost conditions in the tailings would be beneficial. The pore fluid would be immobilized and contact between surface water and the tailings would be limited to the amount of tailings exposed to seasonal freezing and thawing.

Each of these issues is discussed in greater detail in the following sections.

9.2 GROUND THERMAL REGIME

The central issue is whether frozen tailings will thaw with time or whether unfrozen tailings can be made to freeze.

The geothermal conditions at Saskatchewan sites are very close to the balance point between aggrading and degrading conditions. The uncalibrated modelling of the frozen Rabbit Lake tailings indicated that thawing is likely; however, complete thawing could take more than 100 years. Considering that up to 3.5 m of settlement could occur upon thaw, the importance of thermal modelling in the design of decommissioning work is clear. Complete thawing at other sites could take 10 to 20 years.

The technology for ground thermal predictions is well developed. Calibration of the thermal model to measured ground temperatures is essential for reliable predictions, especially when the geothermal condition is so finely balanced. Calibration consists of obtaining measurements of field temperature profiles. The model parameters are then adjusted to obtain a satisfactory match between the measured and predicted temperatures. Since at least one and preferably two years of temperature records are required for calibration, considerable lead time must be provided in the decommissioning studies. Once calibrated, the model can be used with confidence in predictions the thermal effects of various decommissioning alternatives.

The covers (with exception of the vegetation only cover) will reduce the amount of seasonal freezing of the tailings. The reduction occurs because of the insulating nature of the covers, and as a result of decreasing the evapotranspiration heat loss during summer months. The vegetation only cover will tend to increase evapotranspiration losses and increase heat losses from the soil.

The estimated frost depth for each cover was assessed. Equivalent surface temperatures were estimated from the thermal modelling presented in Chapter 4.0. The frost depth was estimated using a simplified thermal model for multilayered soils. The environmental parameters are shown in Table 6.3-3 and the depth of frost is shown in Table 6.3-4. Also shown is the estimated amount of segregational and total heave within the frozen tailings.

The engineered covers almost completely eliminate seasonal freezing of the tailings site. The barrier and subdrainage system is, however, subjected to seasonal freezing and thawing. The drain would freeze seasonally. Spring runoff would be essentially complete before the drain and barrier thawed.

The rock cover limits freezing of the tailings. A vegetated cover (no trees) has little influence upon the depth of freezing as the warming influence of a thickened snow pack is offset by increased evapotranspiration.

9.3 FROST ACTION

The major issue with respect to frost action is predicting whether pore water expulsion features will occur. From observations and analytical estimates, it appears that tailings freeze with a segregated ice content of around 15 to 30 percent, resulting in a seasonal frost heave up to 500 mm for no cover surcharge. The thickness of the engineered covers limits seasonal heave to lesser amounts (Table 6.3-4).

Pore water expulsion features, such as the hummocks at Key Lake, are of concern because of their height (1 to 1.2 m) and the irregular heaving associated with this mechanism, and the tendency to crack and expose the surficial soil. Estimation of the material and drainage conditions under which these features will occur is fairly important to decommissioning design. The theoretical technology for such predictions exists but is not well developed in practice. More field observations are needed.

The frost "pumping" mechanism is speculative at this point in time. If it is a valid mechanism, and 100 mm or more of tailings pore water is added annually to the contaminated fluid balance, it could have a significant impact upon decommissioning design. Thick covers will substantially reduce the potential for frost pumping much as they reduce the potential for frost heave. In the case of the vegetation only cover, any fluid released by frost pumping would be more or less balanced by evapotranspiration, resulting in increased concentration of dissolved constituents near the surface. The increased salinity may be detrimental to the vegetation. In the rock/gravel case, evaporation of the water would be limited and it would be free to flow within the highly permeable cover. Investigation of the pumping mechanism is in the research realm. Directly applicable technology is not available; however, the frost heave technology is closely related. This issue should be put to rest as early as possible in the decommissioning design process.

The magnitude of ice segregational frost heave can be easily observed in the field under various surcharge conditions. Test installations would be relatively easy to construct and monitor.

9.4 THAW CONSOLIDATION

Thawing of frozen tailings will be accompanied by settlement. Settlement could disrupt the cover surface drainage. The tailings are sufficiently permeable that the rate of thaw, rather than the rate of drainage, will control the rate of settlement. The fluid released upon thaw will be introduced into the tailings water balance. Thaw settlement will have an equal effect upon engineered and thin covers. Major differential settlement could crack the barriers.

The technology for estimating the amount of settlement is quite well developed.

9.5 COVER PERMEABILITY

Freezing and thawing increases soil permeability. The increase occurs because of several mechanisms. If sufficient moisture is available, segregational heaving occurs. Even small amounts of heave can create a fissure network that increases soil permeability. If the covers exist in an undersaturated condition, the soil will shrink upon freezing, resulting in a vertical series of cracks that can also affect permeability. The combination of these effects can increase the barrier permeability by an order of magnitude or more.

The barrier will be frozen during spring runoff. Little infiltration would be expected at this time.

9.6 SOIL EROSION

The major effect of frost action upon the potential for soil erosion is the expulsive frost boil. Boils such as those at Key Lake can crack the overlying soil and expose the tailings to wind and water erosion. This mechanism is considered to be a major concern in the case of the vegetation only cover, a lesser concern with the rock only cover and a limited concern for the engineered covers.

9.7 PERMAFROST AGGRADATION

The benefit of freezing the tailings is that the pore fluid is immobilized and prevented from release to the environment. The disadvantage is that heaving associated with development of the frost could disrupt surface drainage.

Conditions at Saskatchewan sites are quite close to the balance between aggrading and degrading permafrost. However, thawed conditions are favoured. It would take a relatively small change in the thermal balance to invoke permafrost aggradation.

There are two basic methods of changing the heat balance to induce permafrost:

- Artificial means.
- Changing the surface conditions.

Artificial methods include active refrigeration either through mechanical air heat exchangers, heat pipes, or active refrigeration. All these may be of limited value for tailings because of cost and long-term care considerations.

The other alternative is to change the ground surface conditions. It was shown in the thermal analysis that by simply increasing the evapotranspiration losses during the summer (high water table conditions) and reducing the depth of snow, permafrost would aggrade. These techniques alone are inconsistent with other decommissioning objectives and are less practical.

One method which shows some promise is the convective rock cover. The convective rock cover consists of a layer of rock which is sufficiently coarse grained that free convective air currents can be established in the interconnected voids.

During the summer, the surface temperature is greater than the temperature at depth. The warm air in the voids remains at the surface and convective heat transfer is low. During the winter, the surface temperature is lower than the temperature at depth; the cooler, heavier air sinks to the base of the rock cover where it is warmed by the soil and subsequently rises. In winter, convective heat transfer is high.

This mechanism has been observed by archaeologists in Siberia, see Rudenko (1970) and Artamonov (1965). Permafrost conditions had preserved ancient bodies buried under a rock cairn acting as a natural refrigerator, see Figure 9.7-1. It is not clear whether the cairn merely preserved general permafrost conditions that were prevalent at the time of burial and have since degraded in adjacent areas, or whether the cairn induced the permafrost. The frozen ground exists at high altitude, but generally the surrounding ground is not frozen. The region is in the Altai Mountains of 49° to 50°N latitude and 86°E longitude.

Application of this method to Saskatchewan uranium tailings piles would require padding of the tailings with soil to provide a working surface and placement of approximately 2 m of coarse, uniformly graded waste rock. Depending upon the gradation of the rock, some processing may be required. A thin surficial layer of finer-grained rock or soil might be required to prevent snow and debris from plugging the voids.

Similarly promotion of freezing ground using air convection through buried casings has been developed by Russian technologists, see Tsytovich (1975). Mukhetoknov (1969, 1971) presented laboratory work, a thermal model and field observations on the effect of convective heat flow in the downstream shoulder of a rockfill dam. The dam was located in a continuous permafrost zone of Siberia where the mean annual air temperature is -8.2°C. Normally, the reservoir water would tend to thaw the permafrost subgrade. However, the convective heat flux in the rockfill was sufficient to maintain the permafrost condition below the dam.

Farouki (1986) summarizes the theory of free convection. Free convection occurs in interconnected, air-filled pore spaces greater than several millimetres across. Above a critical temperature gradient, the convective heat flux increases in proportion to the square of the temperature gradient. The Rayleigh number, Ra, is significant in estimating the conditions under which convection occurs:

$$Ra = \frac{\Delta T \alpha g h K}{a v}$$

where ΔT = temperature difference across the layer

h = thickness of the layer

a = coefficient of volume expansion of the fluid

v = kinematic viscosity of the fluid

α = thermal diffusivity of the fluid

K = intrinsic permeability of the porous material

g = gravitational acceleration

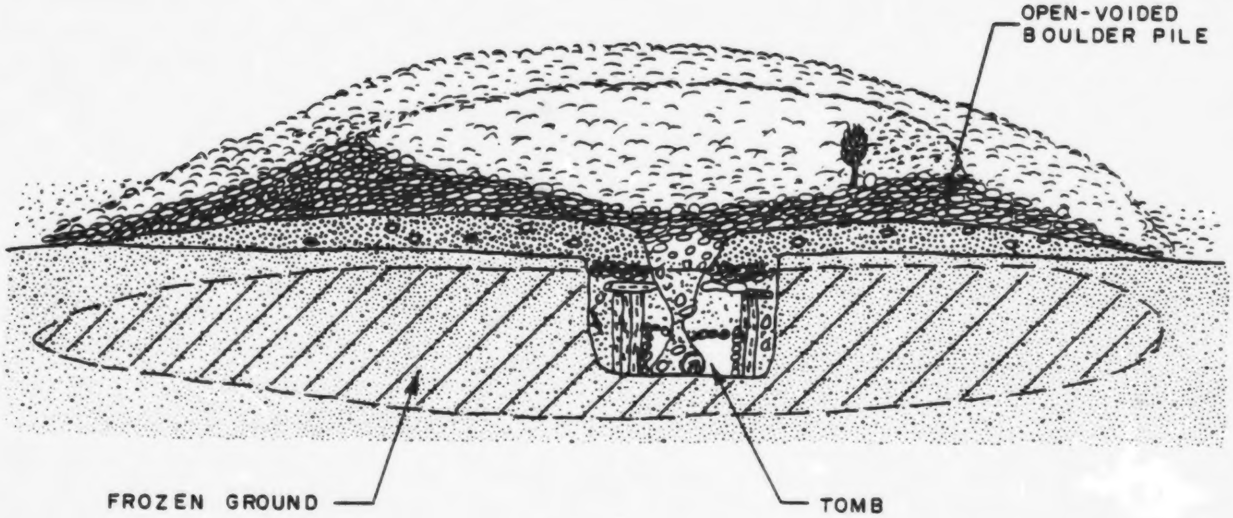

OPEN-VOIDED BOULDER PILE
FROZEN GROUND
TOMB

Figure 9.7-1 Naturally Frozen Tomb in Siberia (Perspective & section sketch from Artamonov, 1965)

Johansen (1975) found that the effective thermal conductivity of the soil is increased as a result of free convection. For values of the Rayleigh number below 40, there is no free convection. For values of Rayleigh number above 40 the effective thermal conductivity increases linearly with the Rayleigh number to a maximum thermal conductivity approximately 2.5 times as large as the conductivity with no convection.

The Rayleigh number increases with increasing temperature difference, layer thickness and the intrinsic permeability of the convective layer.

A simple finite difference thermal model incorporating thermal convection was developed. Rabbit Lake meteorological conditions and tailings properties were modelled. The model used "n" values to simulate ground surface heat exchange. The "n" values were adjusted until a freezing isotherm similar to that predicted by the EBA model (Section 4.0) was obtained.

The effect of various thicknesses of a rockfill cover on the thermal regime was estimated. The results are presented in Figure 9.7-2. The rockfill cover has no effect until it is about 1 m in thickness. The model predicted increased heat loss, however, the loss was insufficient to initiate significant formation of permafrost.

Also shown in the figure is the annual heat flux across the ground surface. The rockfill significantly reduces the heat flux for cover thicknesses greater than 1 m.

The effectiveness of the rock cover does not increase significantly for thicknesses greater than 1 m as the increased thermal conductivity is offset by its increased thickness.

The modelling results show that the convective heat transfer process would operate under Rabbit Lake conditions, however, the initial indication is that it would not be sufficient to freeze the existing tailings substantially.

Although this preliminary theoretical modelling is not very encouraging, it is felt that the potential benefits of a permafrost decommissioning scheme would justify a field test installation. The purpose of the installation would be to observe the thermal conditions below a thermal rockfill. It would consists of installing temperature measurement cables within the tailings and placing various thicknesses of waste rockfill as cover over the tailings. The temperature profiles could then be observed over a period of years to see if permafrost conditions develop.

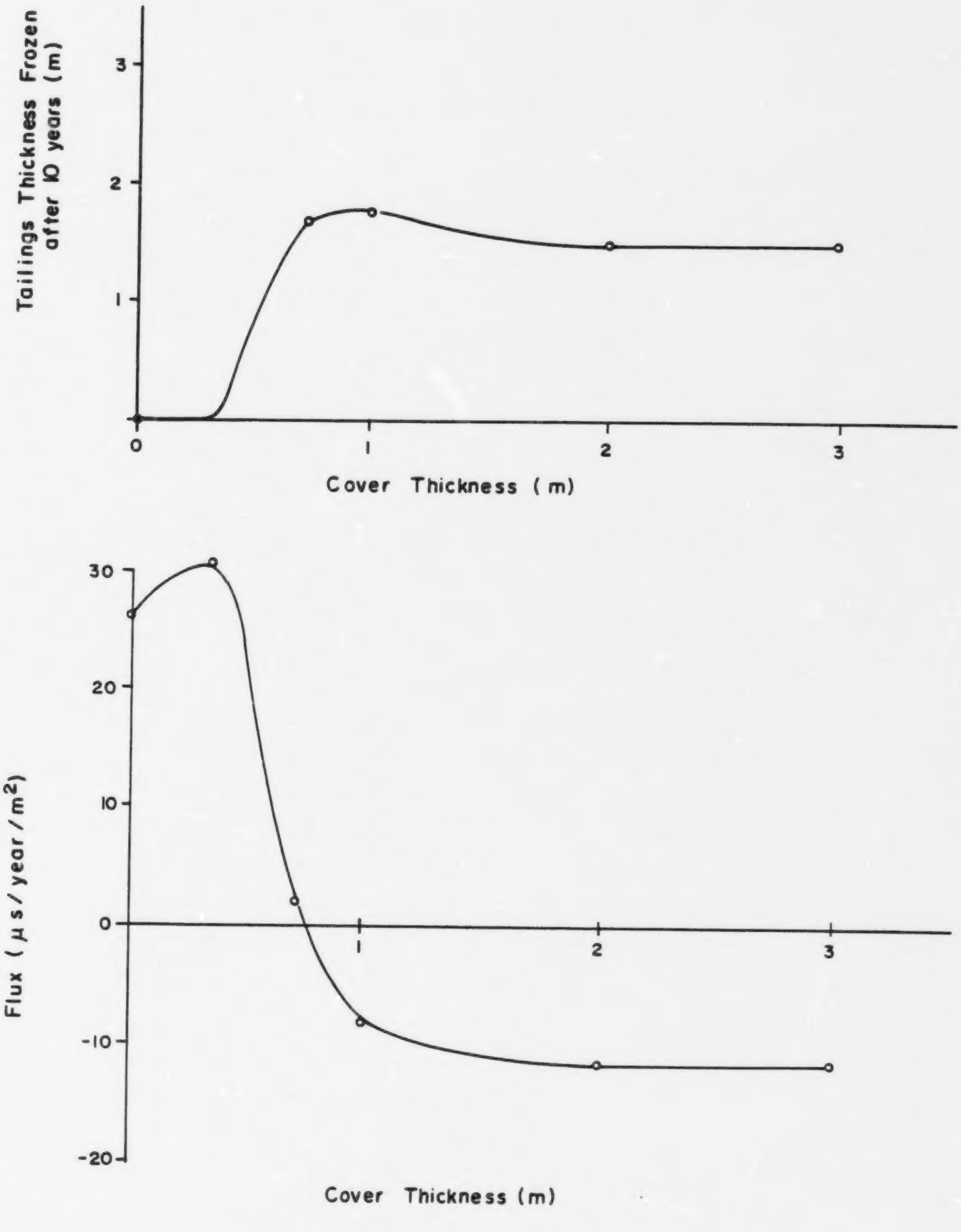


Figure 9.7-2 Effect of a Convective Rock Fill Cover - Rabbit Lake

CHAPTER 10.0
METHODOLOGY FOR INVESTIGATION OF FROST ACTION

10.1 ISSUES

The proposed methodology is a framework for evaluation of the frost effects on tailings. It is not meant to be a "cookbook". A detailed program design would be required to evaluate the specific concerns at any site.

The proposed methodology should be sufficient to address the following issues:

- Thermal destiny. Whether the tailings will ultimately freeze or thaw is a central engineering issue.
- Frost settlement. If frozen tailings exist, what will be the settlement upon thaw?
- Frost heave mechanisms. Will ice segregation or pore expulsions be the predominant heave mechanism? Where might each mechanism be expected to occur?
- Is frost "pumping" a significant process?
- What engineering measures are available to control undesirable frost effects?

The technology available for thermal prediction and frost settlement prediction is well-established and has been used in other engineering applications. The technology available for frost heave prediction is theoretically sound but is yet unproven in the field. Application of this technology will involve a research component. The frost pumping mechanism is speculative. The potential mechanism is clear, however, investigation of the phenomenon is a research activity at this time.

Section 10.2 discusses the field and laboratory data required to address these issues. Section 10.3 discusses the analytical methodology and Section 10.4 discusses the engineering design considerations.

10.2 FIELD AND LABORATORY DATA REQUIREMENTS

10.2.1 GENERAL

Substantial information exists on most of the tailings deposits, however, it is insufficient to address the frost effects in detail. More information would be required. The information requirements are presented in three components required for the thermal characterization, frost heave and frost pumping estimates.

10.2.2 THERMAL COMPONENT

The required field data consists of:

- Stratigraphic characterization of the tailings, particularly with respect to the presence and extent of frozen tailings.
- Characterization of the basic moisture content, density and mineralogical characteristics of the tailings.
- Characterization of the thaw-settlement properties of frozen tailings.

- Determination of ground temperature profiles of the frozen and unfrozen tailings over a period of at least 1 year and preferably 2 years.
- Water table elevations.
- Qualitative assessment of the site environmental conditions (shading, sheltering, snow conditions, etc.).

The required laboratory testing consists of:

- Thaw-settlement testing of frozen core samples.
- Classification testing (moisture content, gradation, density, etc.).
- Optional thermal conductivity testing to confirm published conductivity relationships for high moisture content, high gypsum content tailings.
- Optional unfrozen moisture content testing to confirm published unfrozen moisture content relationships for high moisture content and high gypsum tailings.

10.2.3 FROST HEAVE COMPONENT

The major issue is to identify the soils which are susceptible to ice segregational frost heave and those which are susceptible to heave by pore water expulsion. Relationships exist for conventional soils at low moisture contents. Indications are that very high moisture content soils, such as tailings, may be more prone to pore water expulsion.

Field and laboratory testing are suggested in addition to thermal data required in Section

10.2.2. The field work would consist of:

- A series of heave gauges so that the heave at various depths can be monitored over a freezing season. The gauges would be monitored by level survey techniques.
- Piezometers installed in the soils so that pore water pressures in advance of the freezing front can be monitored. A rise in pressure would suggest pore water expulsion. Stable to dropping pressures would suggest segregational heave.

Laboratory testing would consist of:

- Frost cell tests to determine whether water expulsion or attraction happens in high moisture content tailings at various overburden pressures.
- Frost heave testing to determine ice segregation ratio (Hwang method) or ice segregation potential (Konrad-Morgenstern method).

10.2.4 FROST "PUMPING"

The frost pumping mechanism is somewhat speculative (Section 6.4). Field investigations would be in the realm of applied research. The question is whether water from melting of segregated ice formed during frost heave can be released to the surface, or whether it will be redistributed within the soil structure.

Two field approaches to the problem are available. First, moisture density access tubes could be installed through the frost into the underlying soil. Moisture content profiles would be obtained at the end of the winter after segregational freezing has accumulated the maximum amount of moisture. The tubes would be read at intervals during the thaw period. If the overall moisture remains the same, pumping is not an issue. If the moisture profile decreases substantially before the frost is completely thawed (i.e., it must be upward drainage), the frost pumping is a valid mechanism. The tubes would be installed in conjunction with temperature measurement cables and piezometers.

A second potential method is a reverse ring infiltrometer test. A ring would be inserted into the tailings surface to a depth of about 300 to 500 mm before freeze-up. Just before spring, any snow accumulated would be cleaned out of the ring and it would be fitted with a lid to control evaporation. Any moisture flow to the surface would then be observed within the ring.

This phenomenon could also be investigated in frost cell tests. Samples would be frozen under open system conditions and allowed to heave. They would then be thawed and the amount of water liberated observed. The tests would have to extend for several freeze-thaw cycles.

10.3 ANALYSIS

10.3.1 THERMAL ANALYSIS

A thermal model capable of modelling complex heat exchange conditions at the ground surface is required. The data requirements have been addressed fully in Chapter 4.0. The source of data is:

- Meteorological conditions - from published records.
- Site environmental data - preliminary information from site observations.
- Thermal properties - from laboratory testing and classification tests with published correlations.

The model would be calibrated with the measured ground temperature profiles. Thermal properties and site environmental factors could be adjusted until a match between the predicted and observed temperatures was obtained. This is an essential step. The thermal conditions at the Saskatchewan sites are very close to the dividing line between aggrading and degrading conditions. Predictions based upon first estimates of ground surface heat exchange conditions and soil thermal properties would not be adequate. After calibration, the model could be used to extrapolate future thermal conditions. In addition, it could be used to assess the thermal impact of any engineering measures (covers, etc.).

10.3.2 THAW SETTLEMENT

Settlement of frozen tailings upon thaw is a concern. For example, it is estimated that up to 3.5 m of settlement of the frozen Rabbit Lake tailings would occur upon thaw. The estimated rate of thaw is very slow and would likely occur over a period of tens of years. The thermal modelling discussed in the previous section will estimate whether thawing occurs and at what rate. The thaw consolidation tests in conjunction with the predicted thawing rate can adequately predict the amount and rate of thaw settlement. In addition, the amount and rate of pore fluid release can also be estimated.

10.3.3 FROST HEAVE

The central frost heave issue is whether pore water attraction or expulsion conditions will prevail and under what conditions each may be expected. This information should follow directly from the frost cell testing. The effects of cover on controlling expulsion heave can also be addressed. Where ice segregation heave is anticipated, the amount of heave can be estimated from the Hwang or Konrad-

Morgenstern method and from direct extrapolation of field heave measurements. Cover and final drainage design must consider the potential heave and probable locations of accentuated heaves.

10.3.4 FROST "PUMPING"

Should the field research show that frost pumping is a credible mechanism, upper bound estimates can be obtained from ice segregational heave theory. As an upper bound, one would assume that all segregated ice is released following thaw as free fluid and that none of the segregated ice is absorbed into the soil matrix.

10.4 DESIGN CONSIDERATIONS

The major design considerations are:

- Surface distortion by heave or settlement.
- Pore fluid transport.

Decommissioning will require grading of the tailing surface so that positive drainage is maintained. Thaw settlement or major frost heaving could disrupt this drainage.

Methods to prevent thawing are available. They consist primarily of passive refrigeration or snow clearing techniques. They are costly and require ongoing maintenance. The appropriate technology is to estimate the amount of settlement that may occur and design the drainage system to accommodate the settlement.

Frost heaving by ice segregation could result in estimated heave of around 600 mm, depending upon groundwater and surcharge conditions. Variability in subsurface and in water table conditions will result in variable heaving. It is not expected that this amount of heave will be significant with respect to decommissioning design.

Frost heaving by pore water expulsion is of greater concern because of the greater amount of heave and its hummocky nature. Heaving can be controlled by such measures as underdrainage to relieve excess pore water pressures and/or surcharging. Any engineering control measure will require an estimate of where and when the expulsion heaving may occur.

Pore fluid transport to the surface will be contaminated. If a cover design incorporating "clean" runoff is used, separate drainage systems will be required to collect and dispose of the pore fluid. If the surface water is treated as "dirty" water in any case, no special provision needs to be made. Estimates of the amount of pumping would, however, be required in order to estimate environmental loadings.

CHAPTER 11.0
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